Improving the Use of Commercial Building HVAC Systems for Electric Grid Ancillary Services

For Lawrence Berkeley National Laboratory

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Massachusetts Institute of Technology

1/21/2016

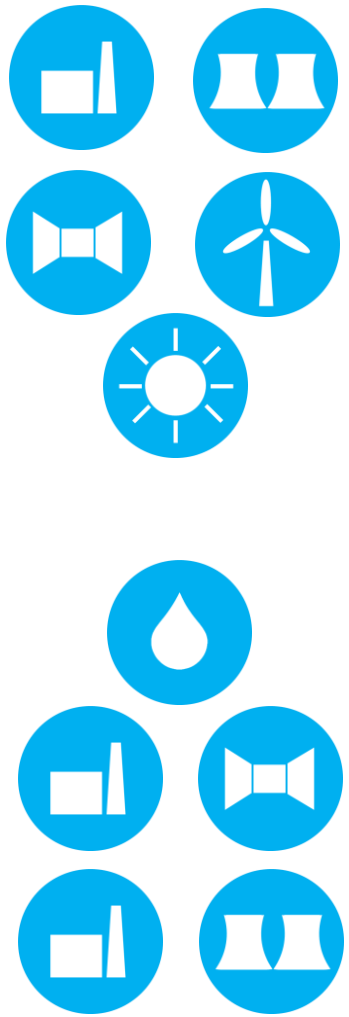
Agenda

Background and Research Introduction

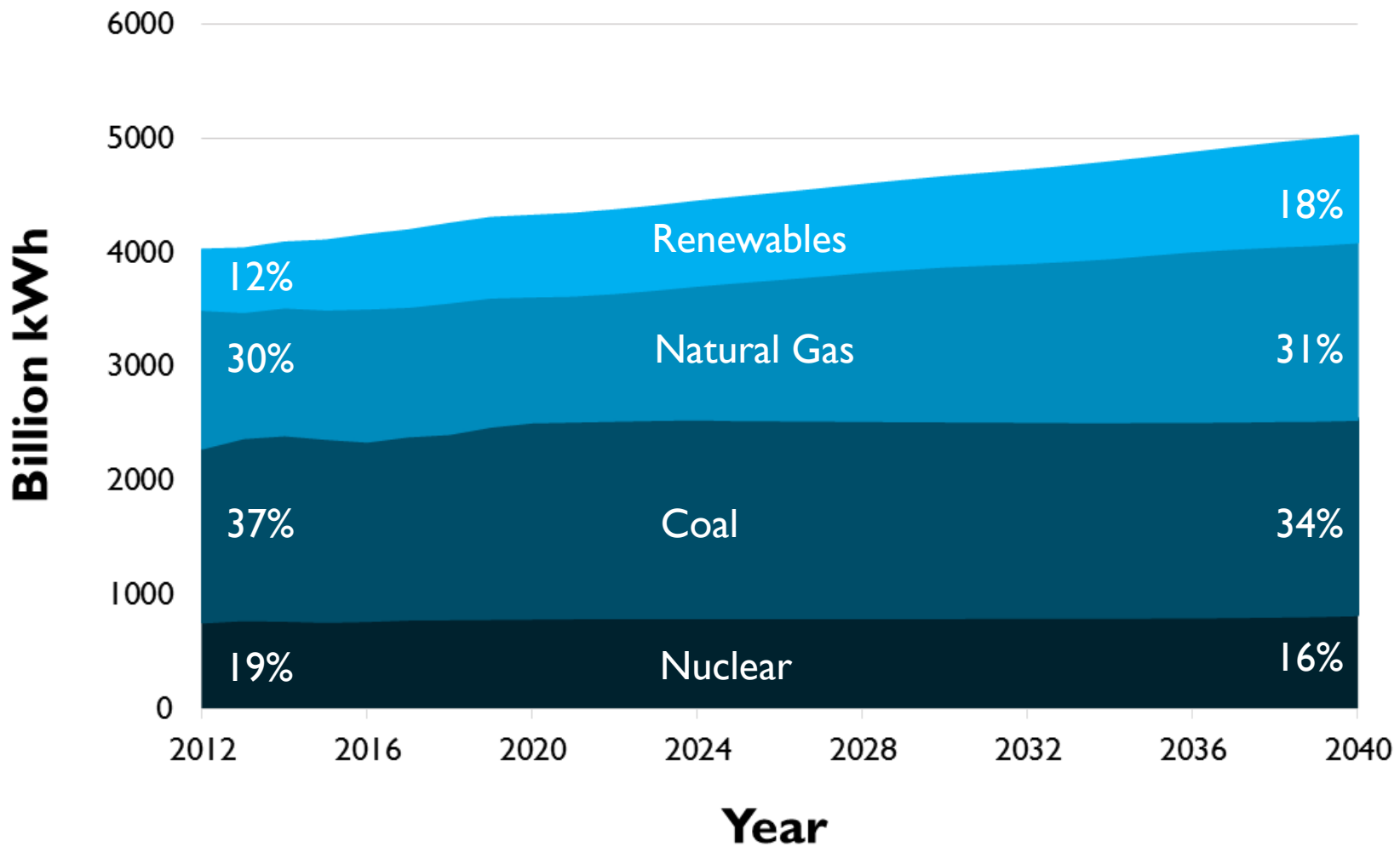
Overview of Selected Work

Questions and Discussion

Current Electric Grid

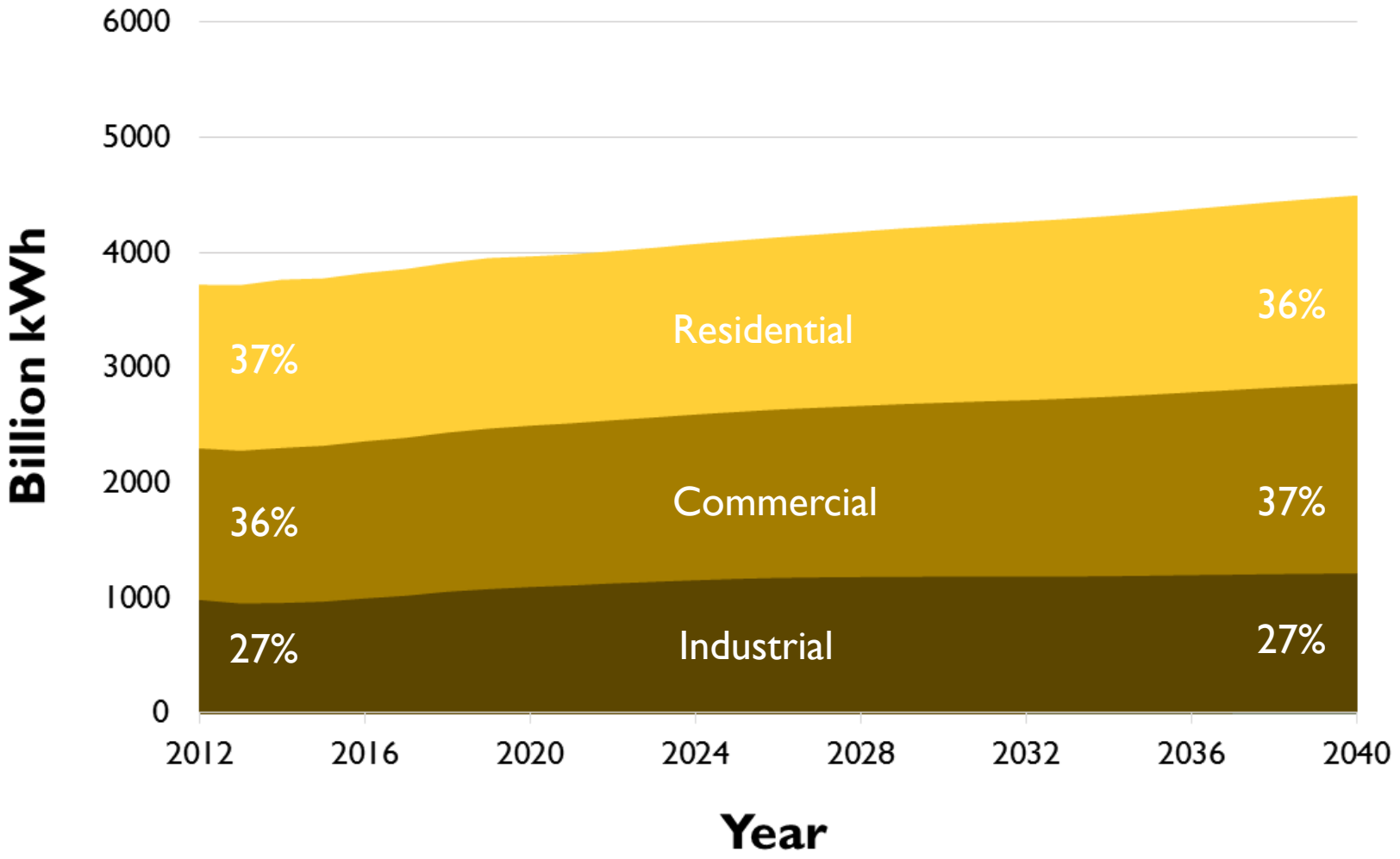


Generation
(Supply)

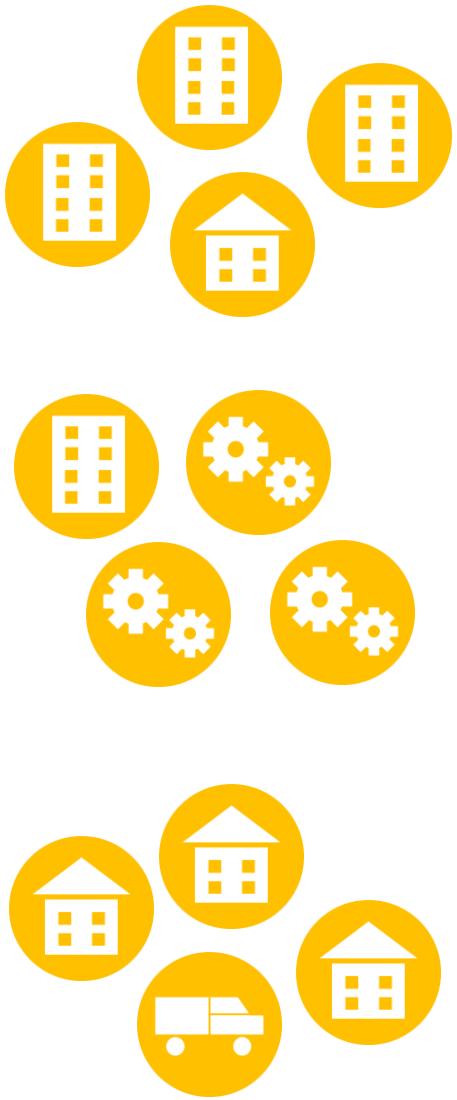


(EIA 2015)

Current Electric Grid

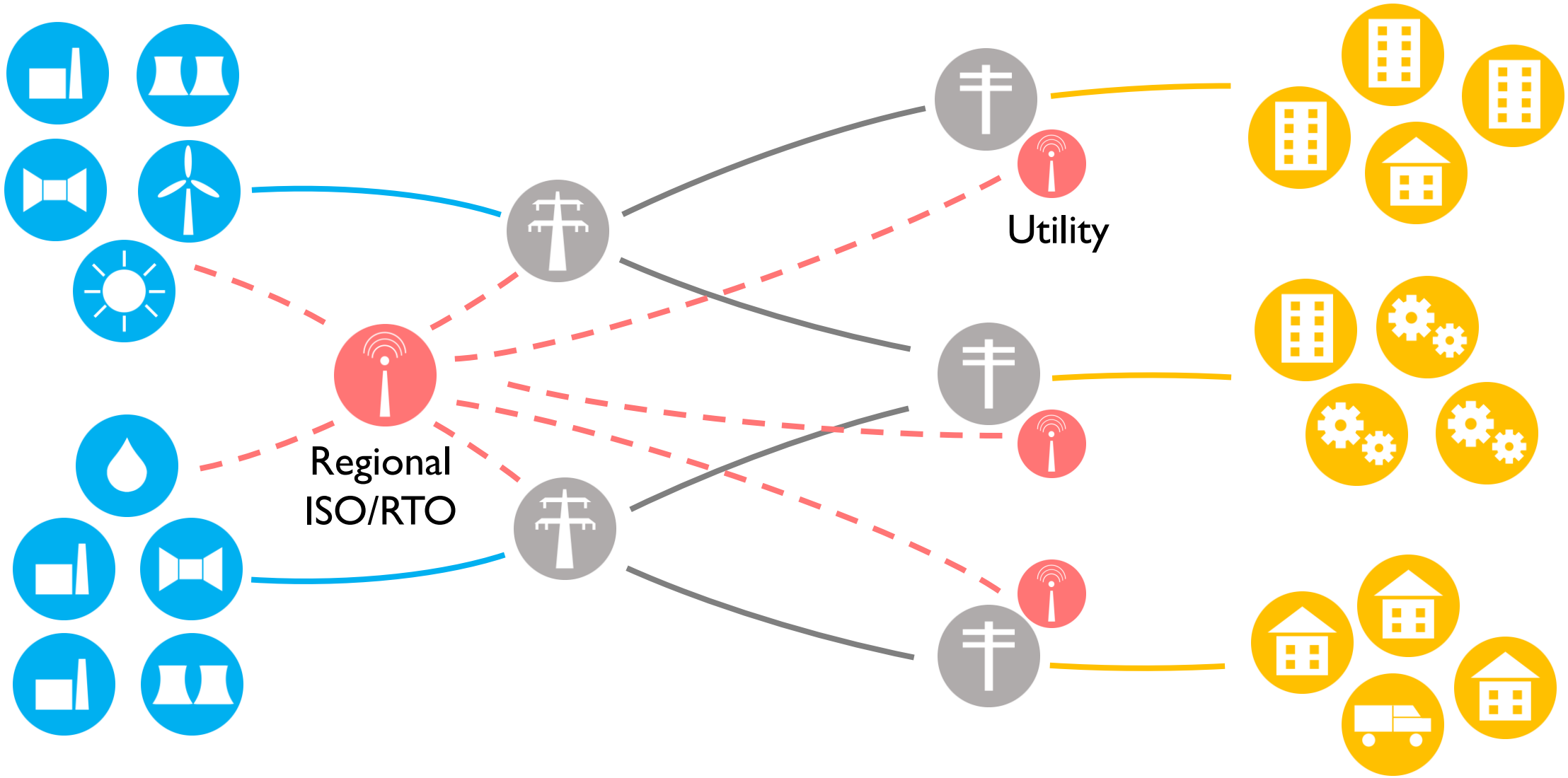


(EIA 2015)

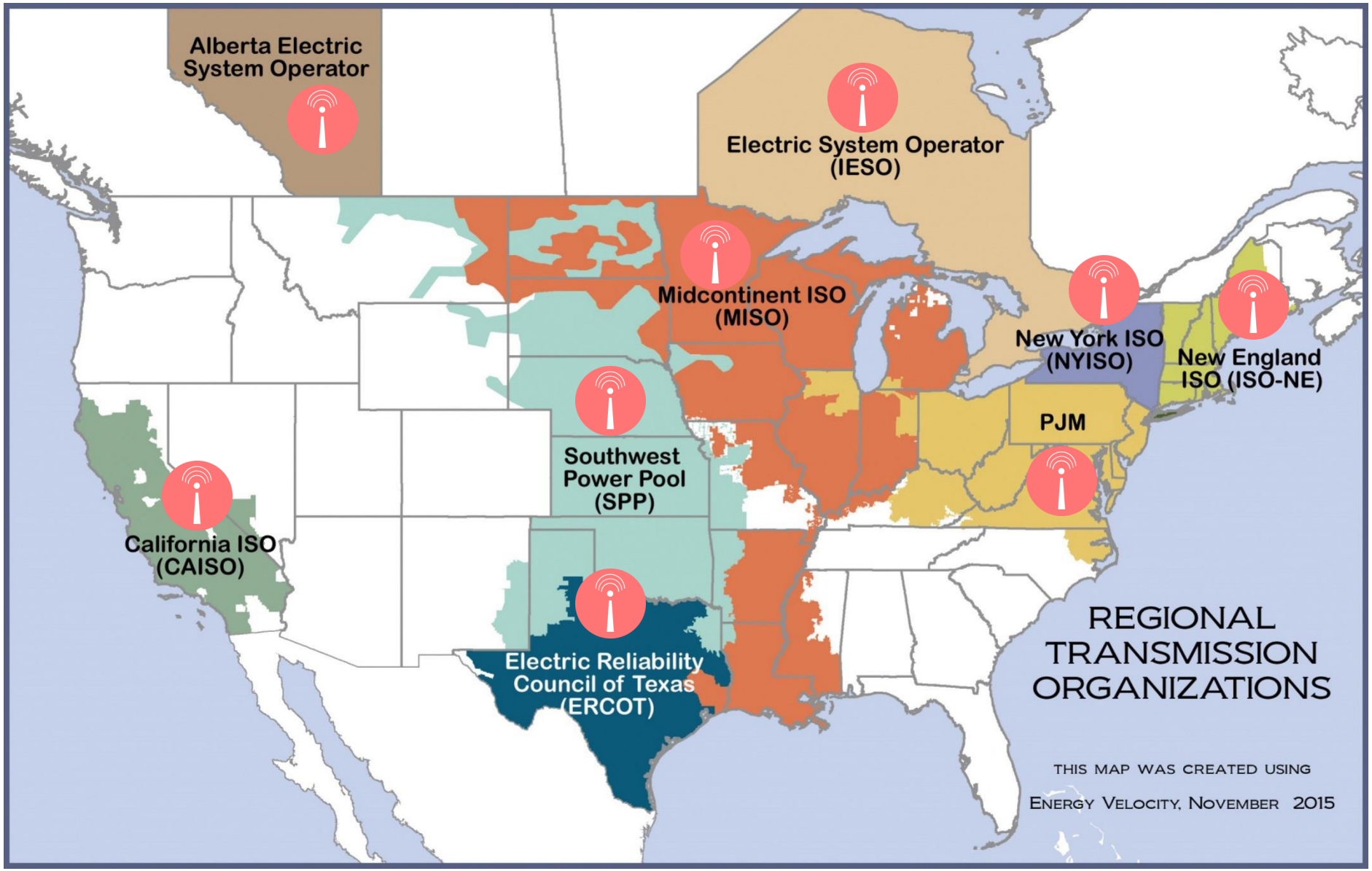


Consumption (Demand)

Current Electric Grid



Current Electric Grid



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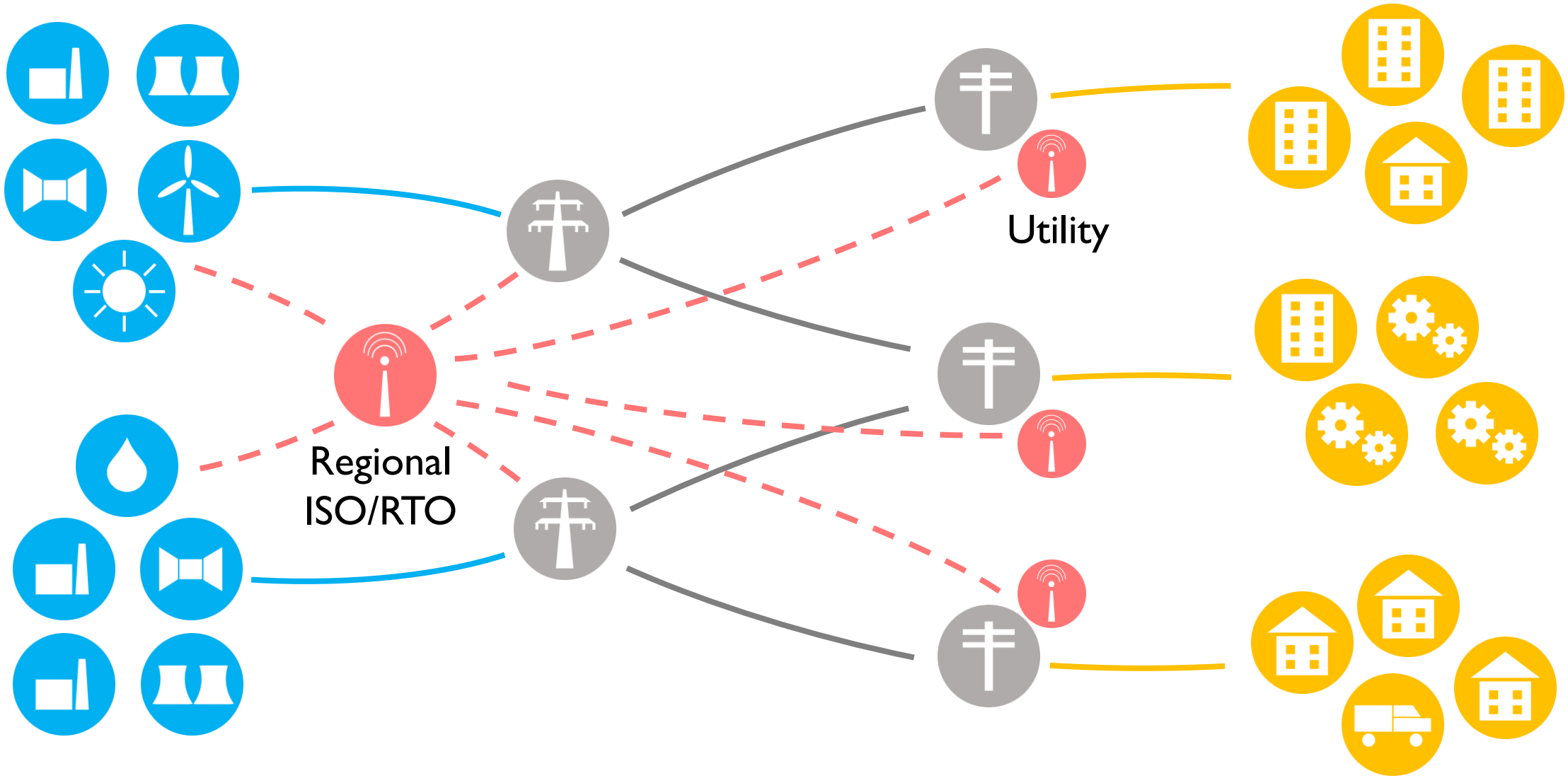
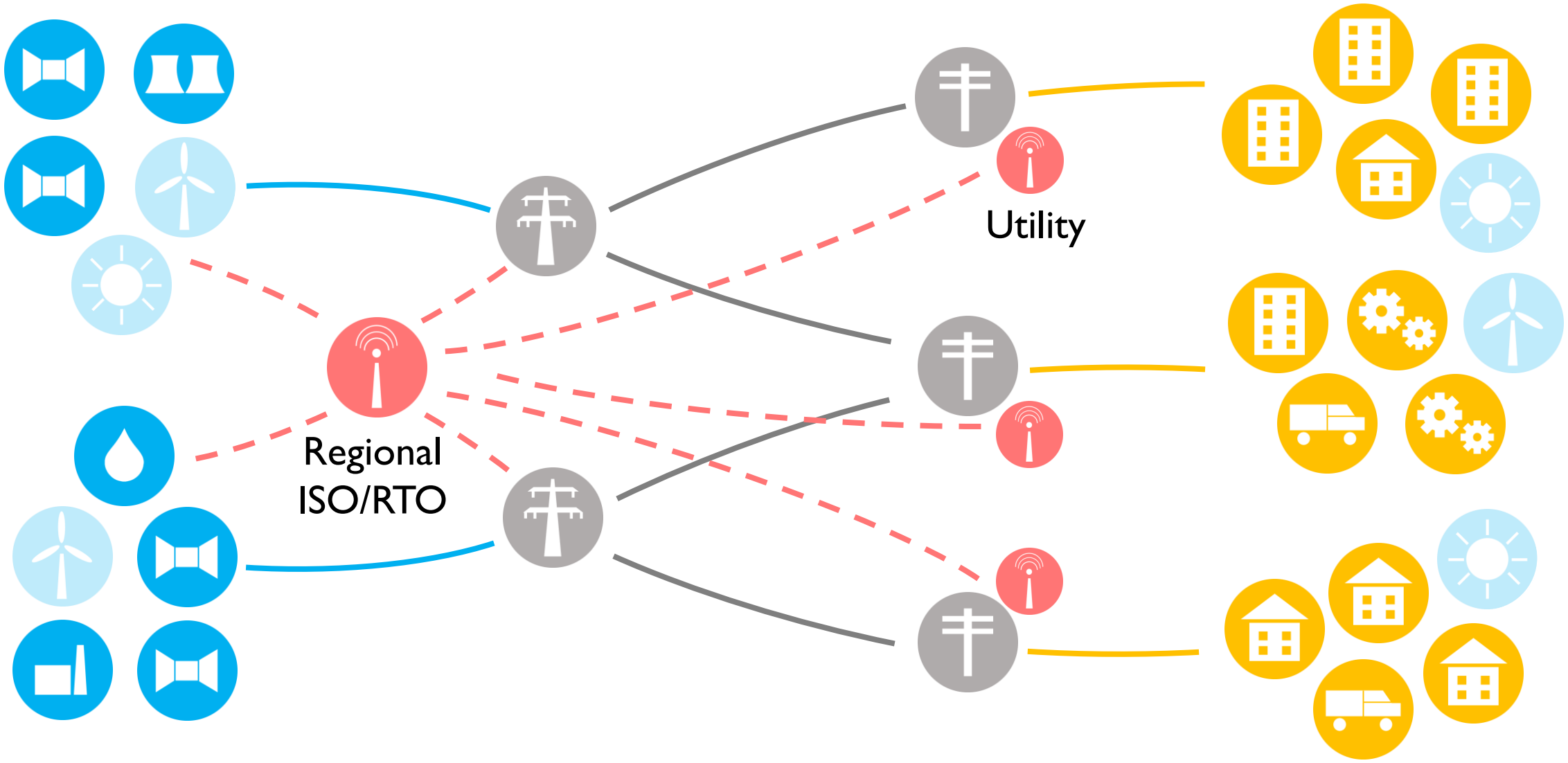
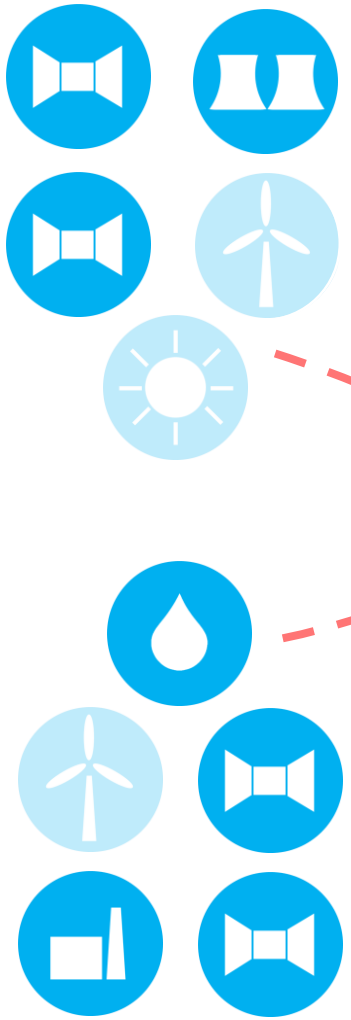


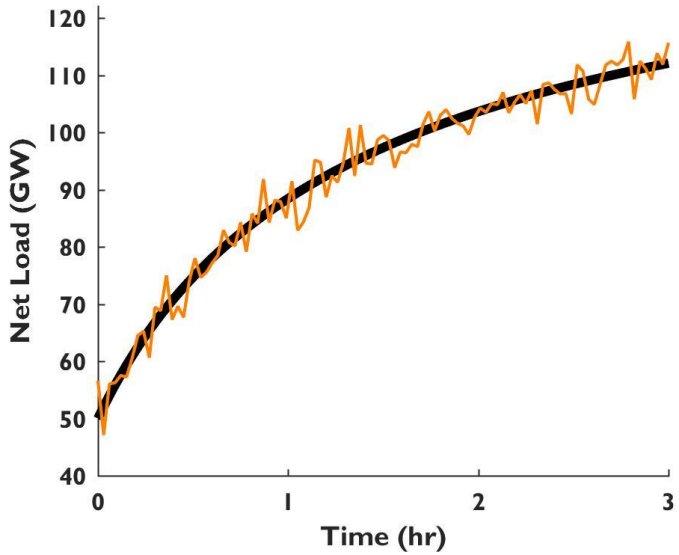
Future Electric Grid

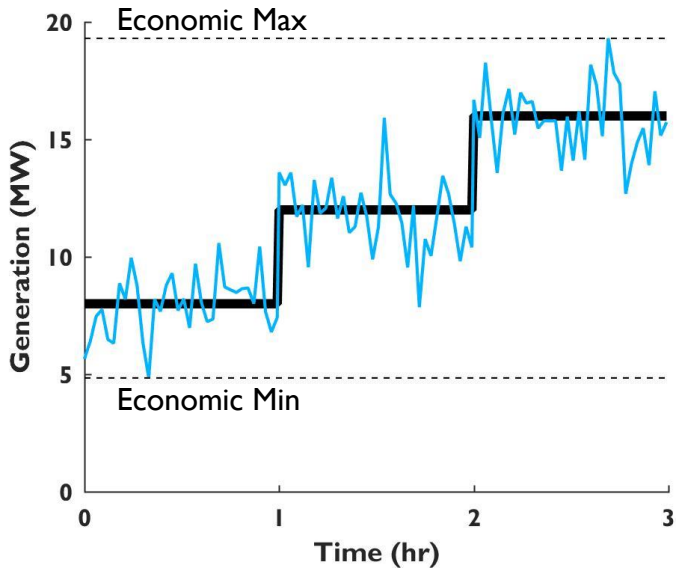


Ancillary Service Types

Regulation





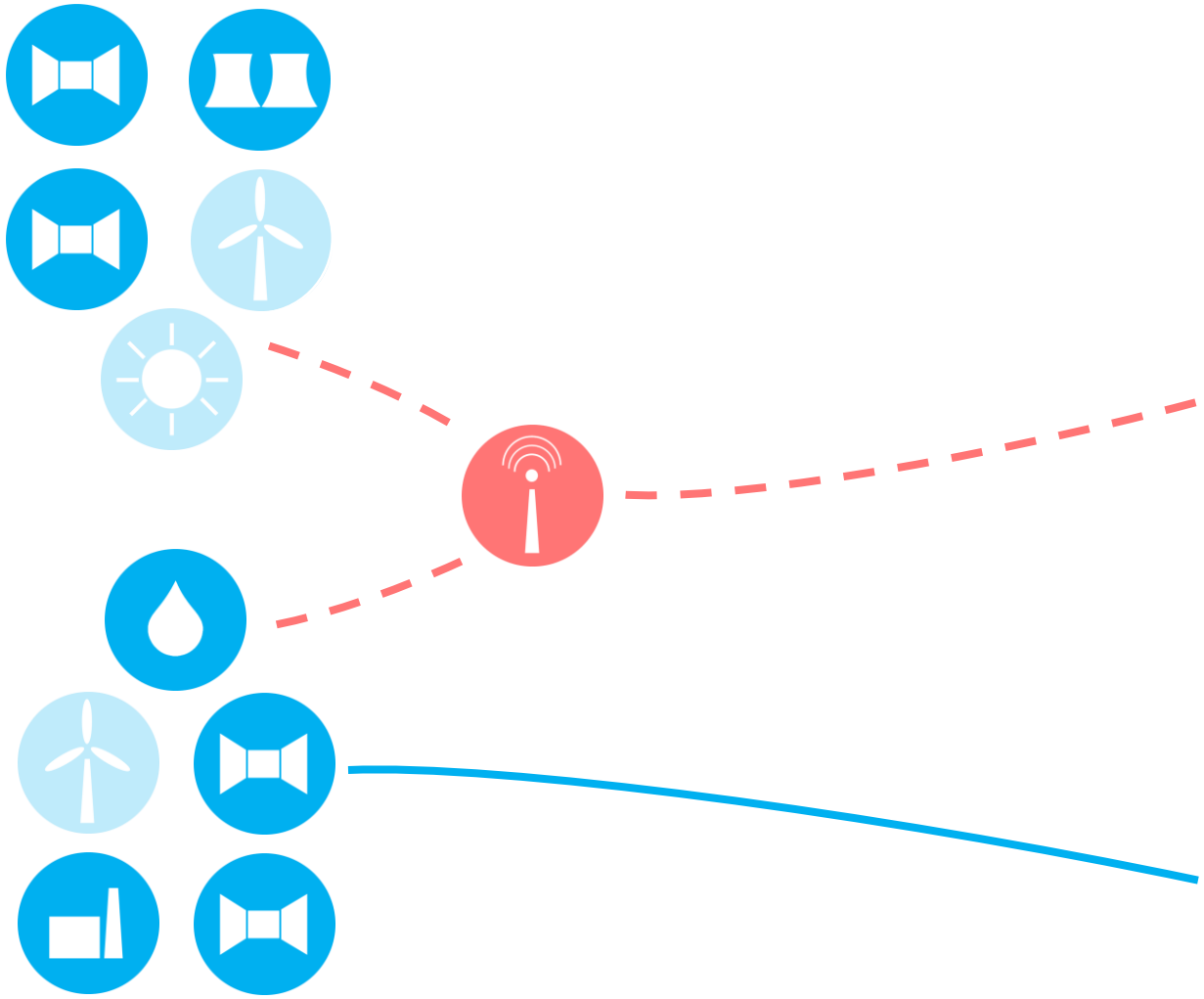


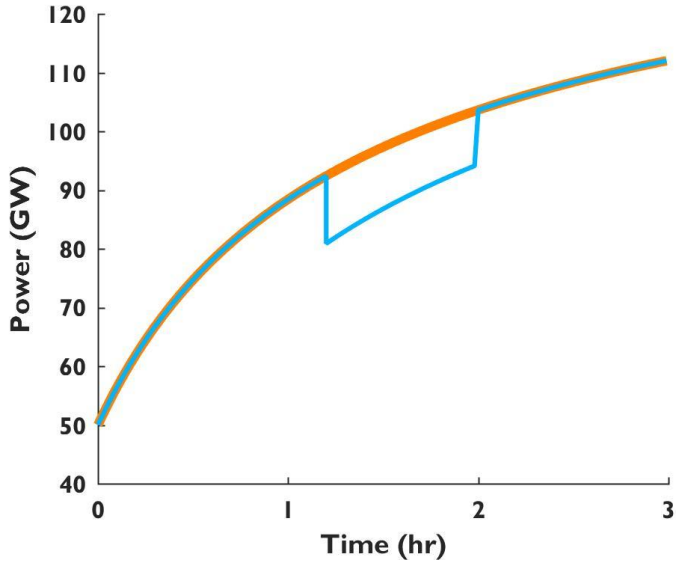
Hr 1
Reg Up Capacity

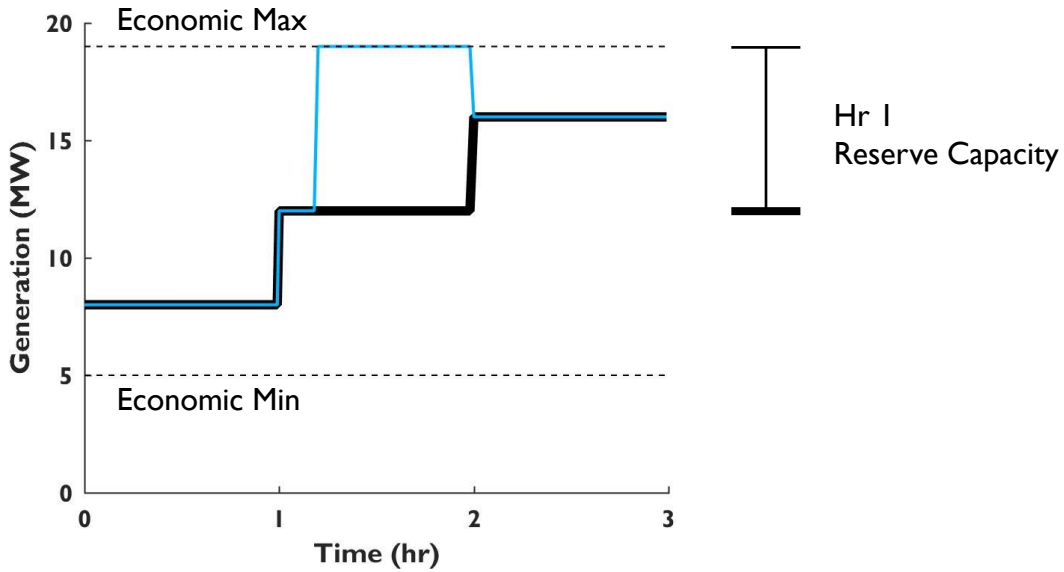
Hr 1
Reg Down Capacity

Ancillary Service Types

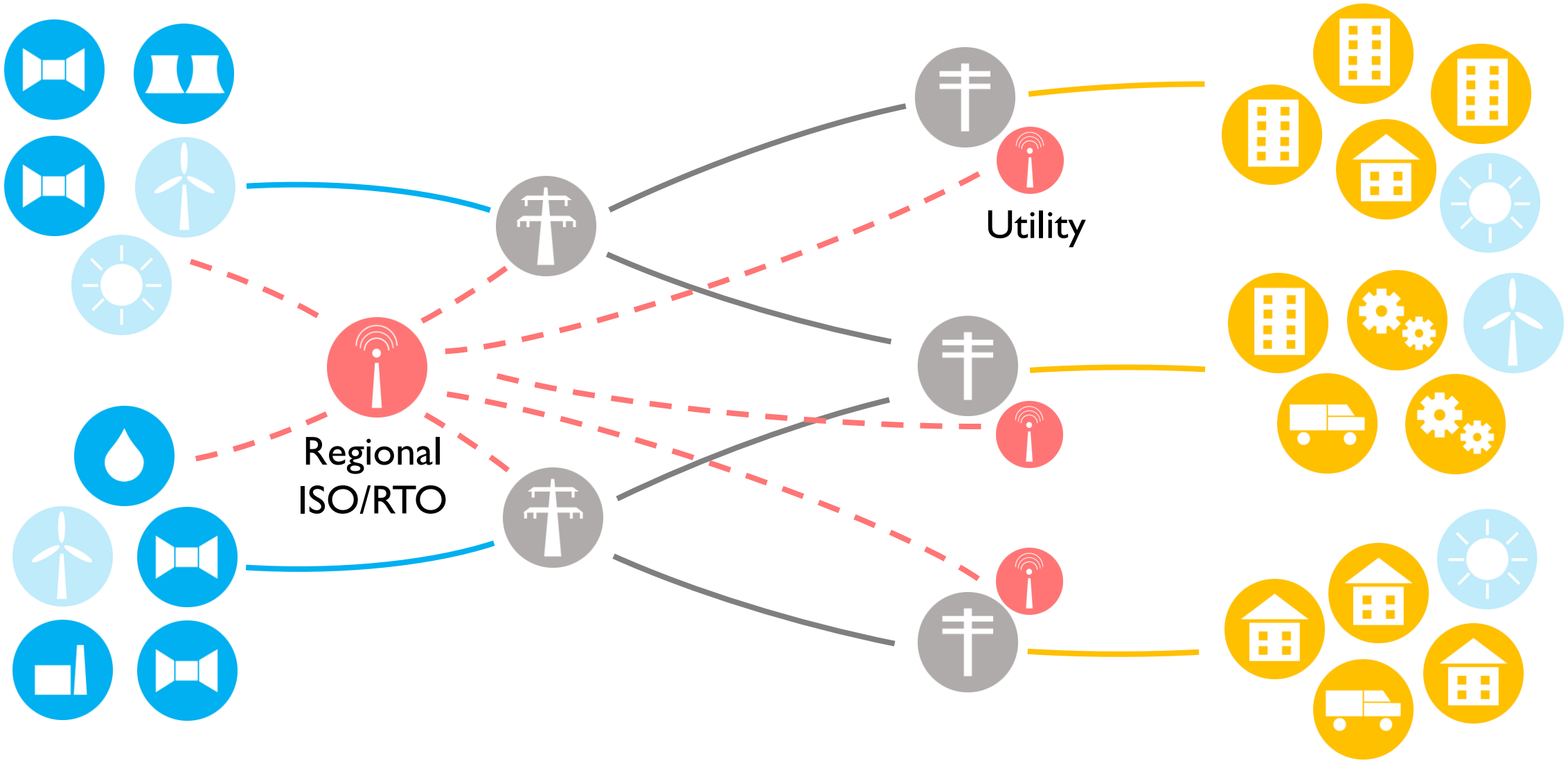
Reserves



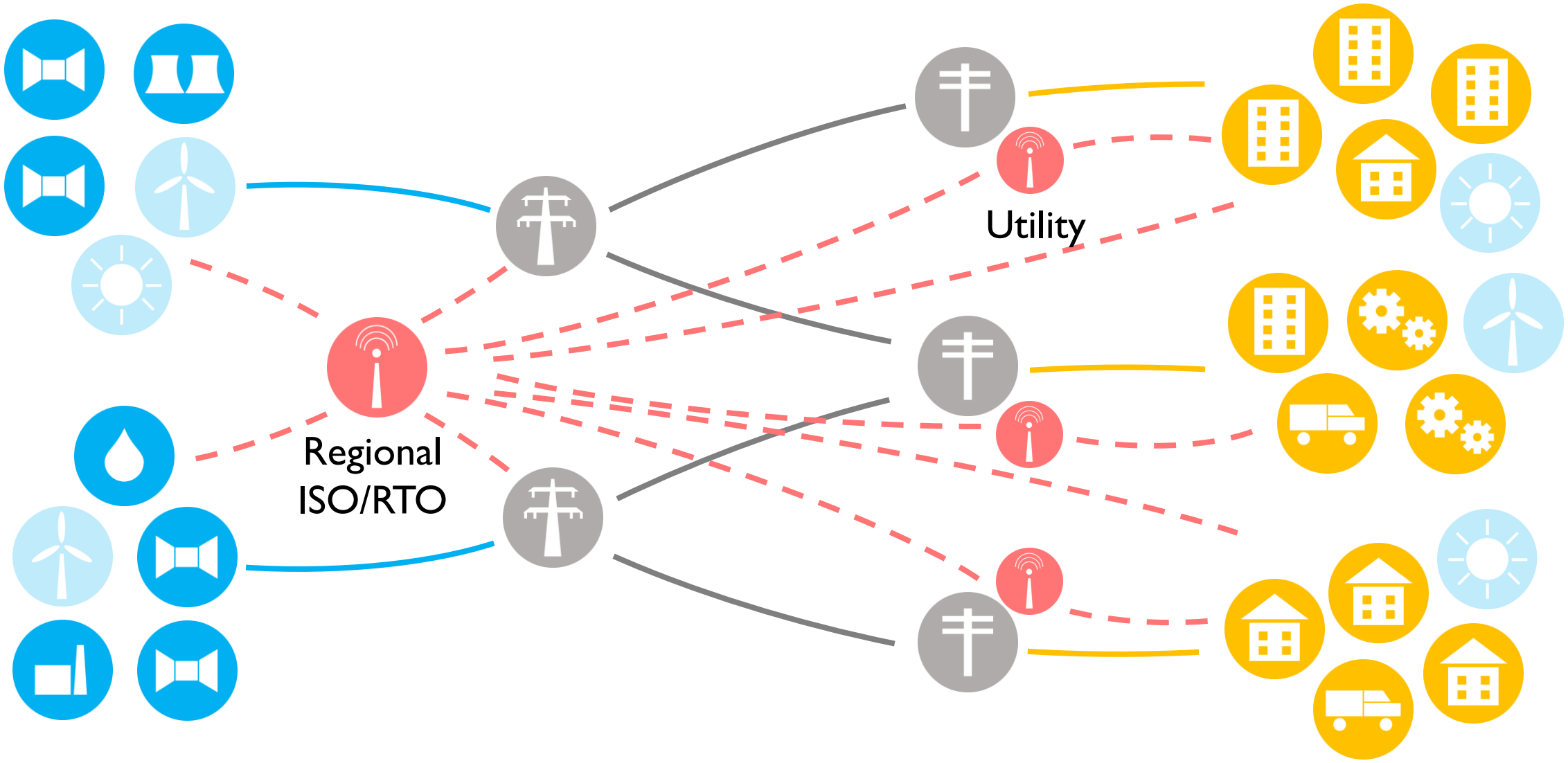




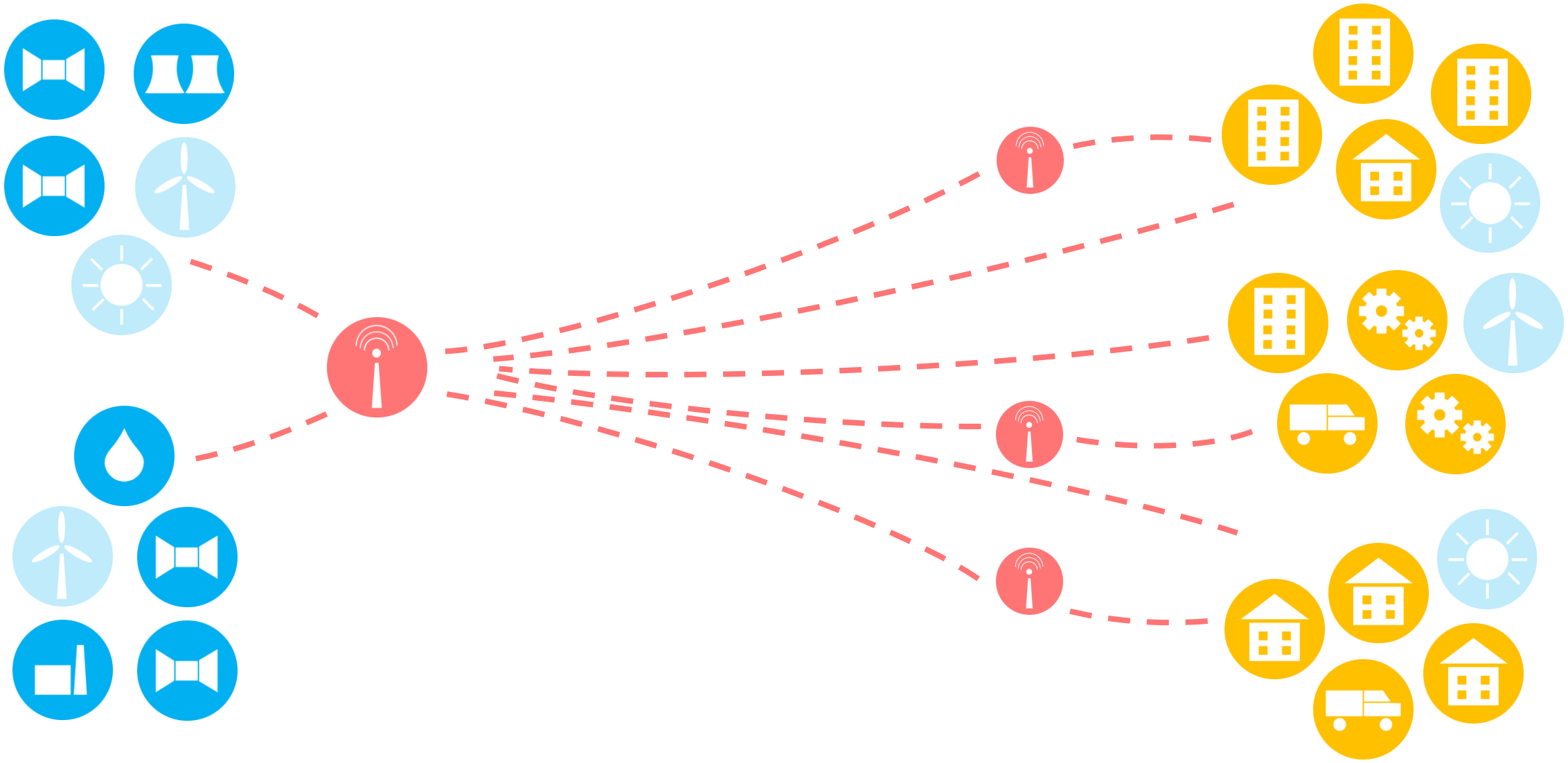
Future Electric Grid



Future Electric Grid with Demand Response

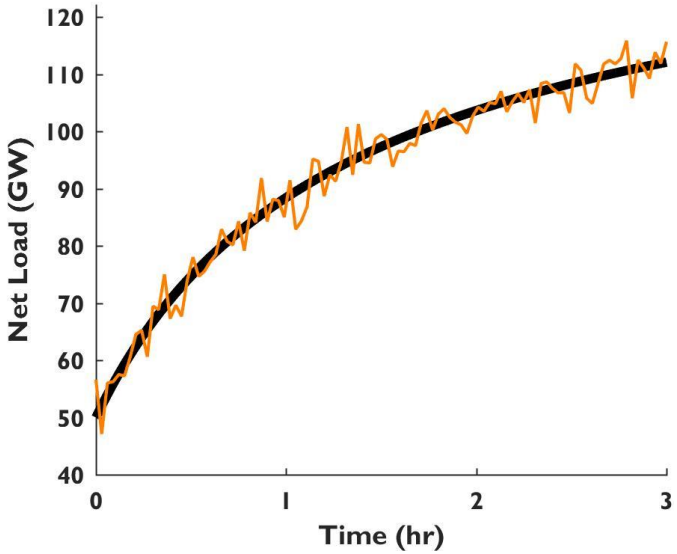


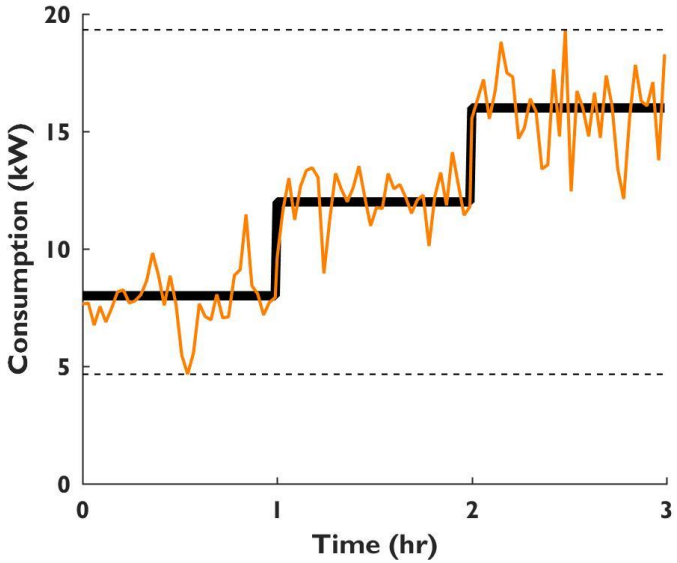
Demand Response (DR)

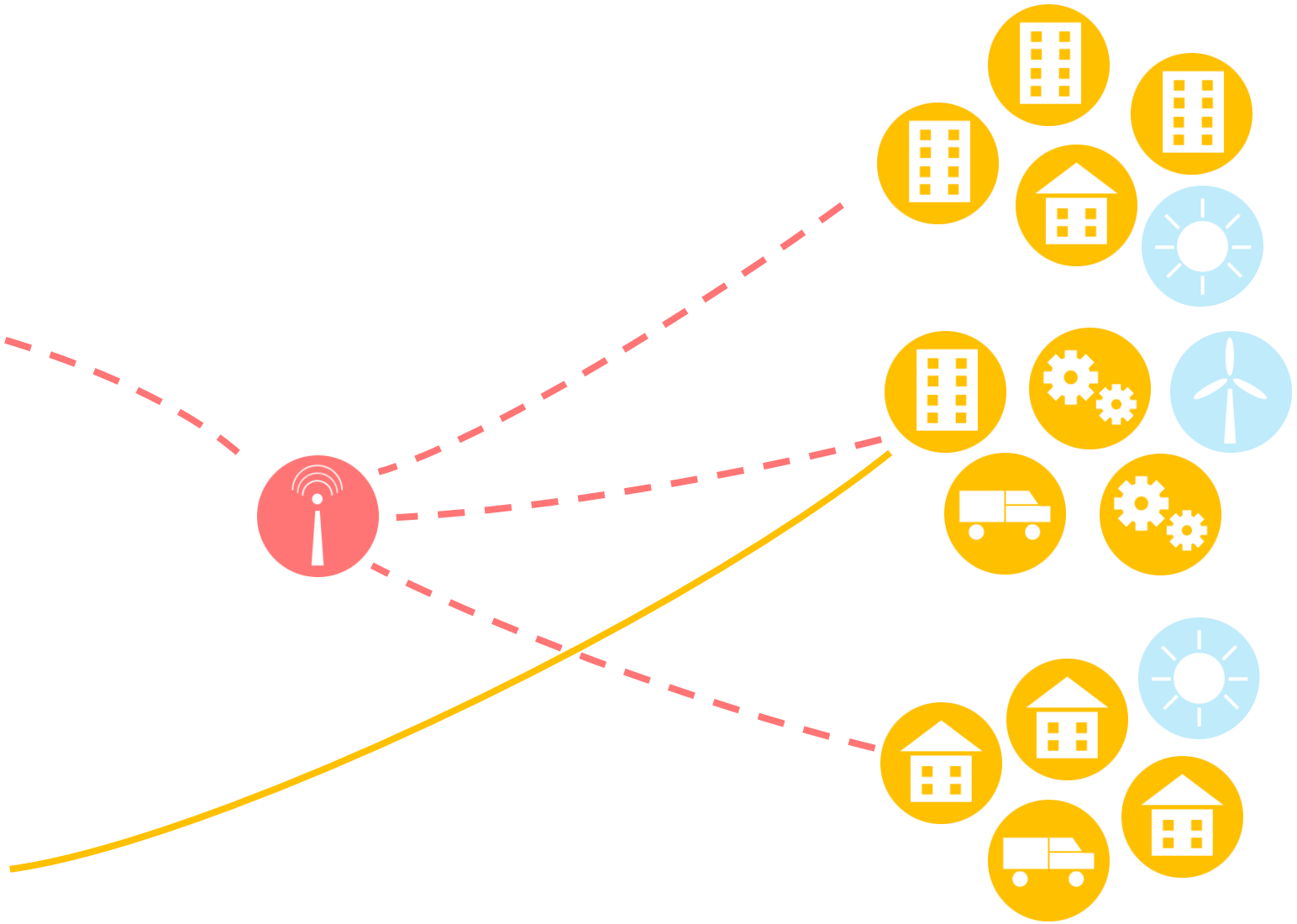


Ancillary Service Demand Response

Regulation

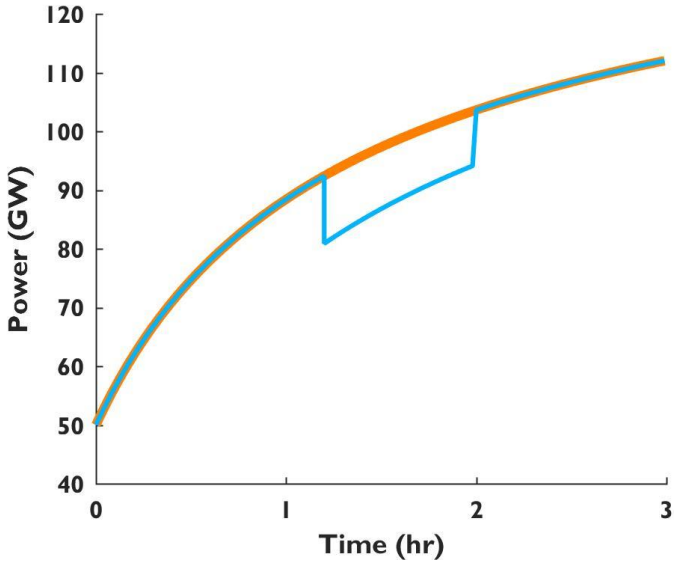


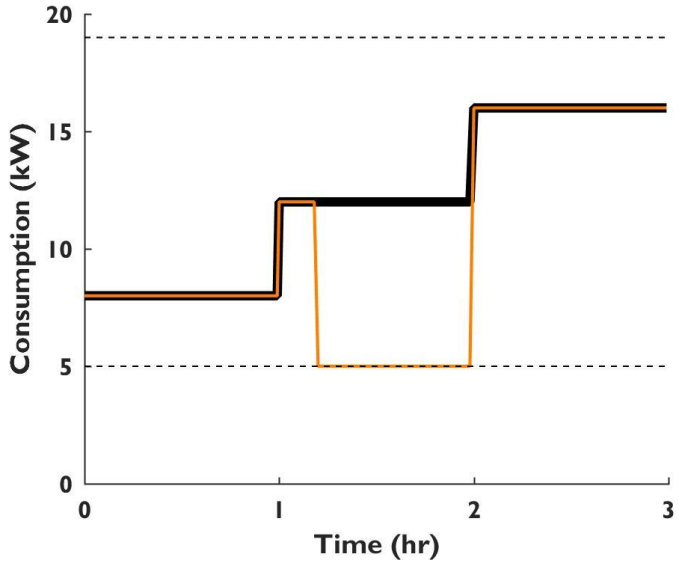


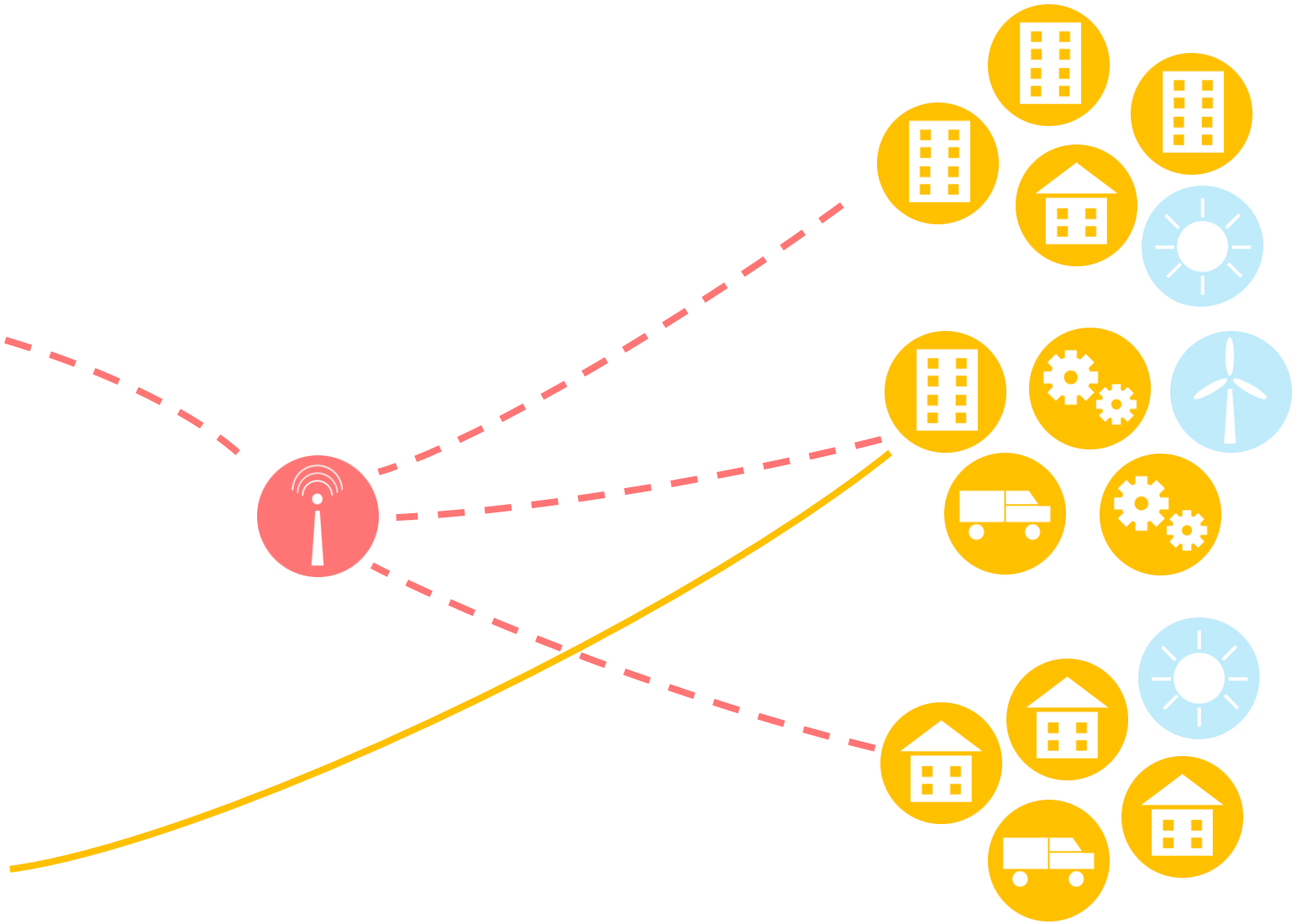


Ancillary Service Demand Response

Reserves

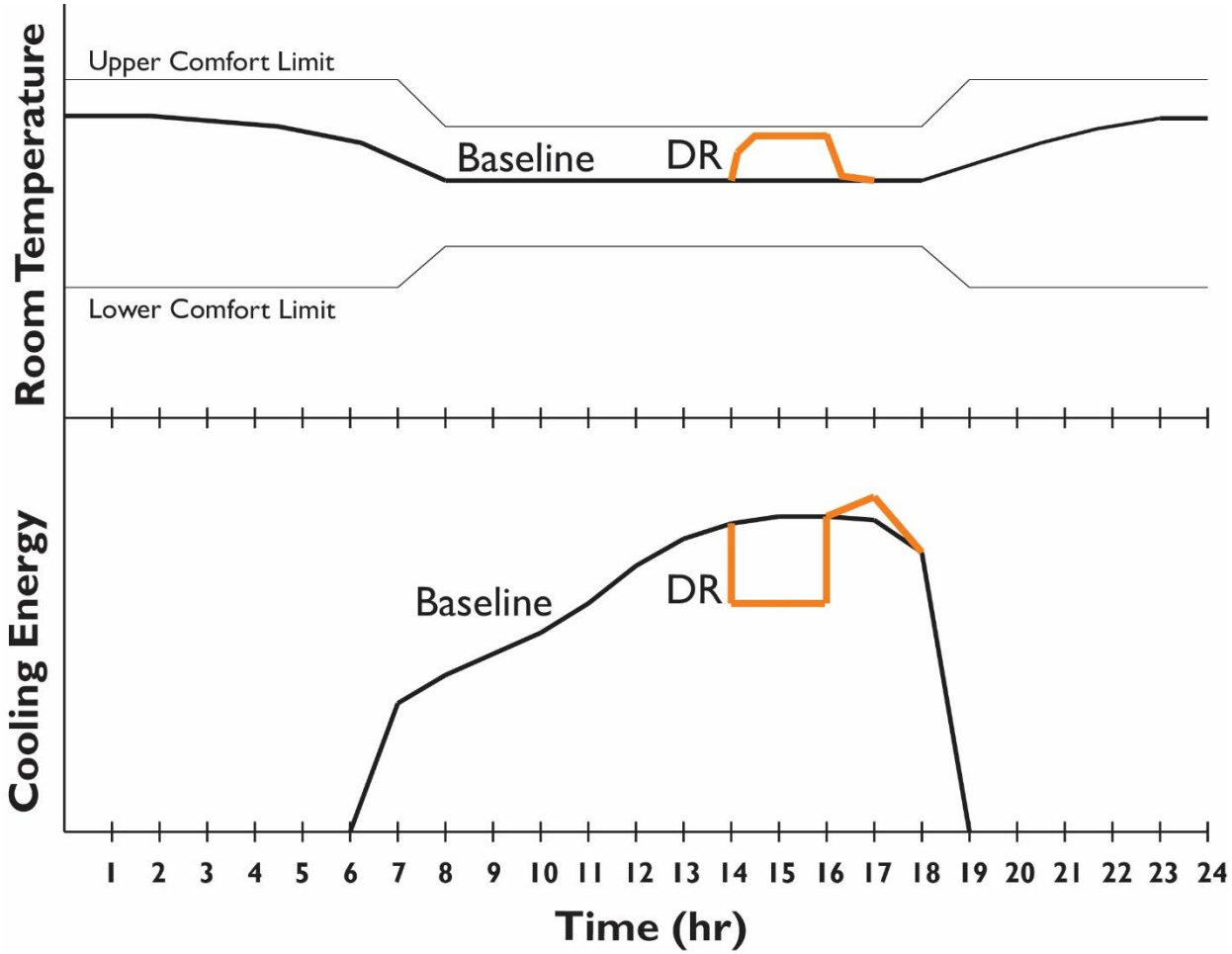






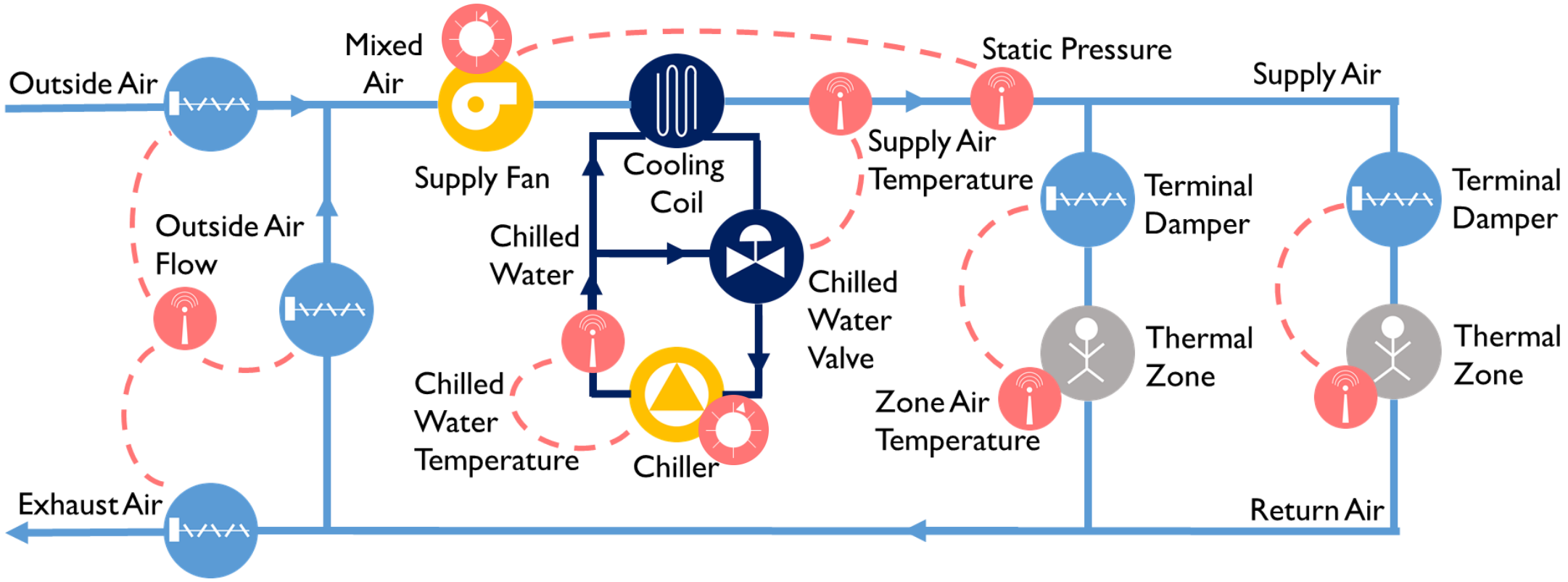
Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage



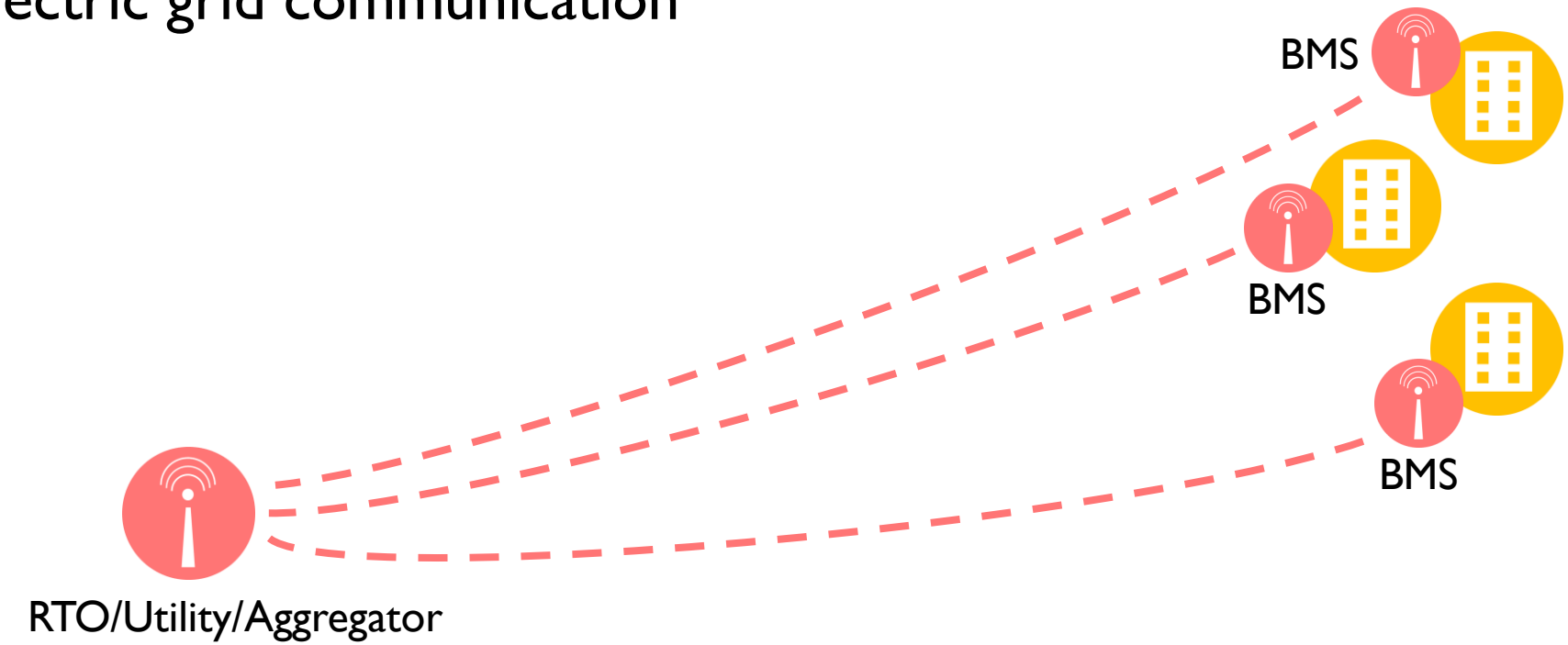
Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage
2) Compressors, fans, and pumps with variable speed drives (VSD)



Use Commercial Heating, Ventilating, and Air-conditioning (HVAC) Systems

1) Link electric consumption to thermal energy storage
2) Compressors, fans, and pumps with variable speed drives (VSD)
3) Building management systems (BMS) allow for individual building HVAC control and electric grid communication



Research Questions

1) How do HVAC systems provide ancillary services?

2) Can buildings optimize a portfolio of ancillary services?

3) Is there a price for providing ancillary services?

4) Does HVAC ancillary service provision scale with other energy storage?

Research Questions

1) How do HVAC systems provide ancillary services?

   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?

   Multi-market Optimization

3) Is there a price for providing ancillary services?

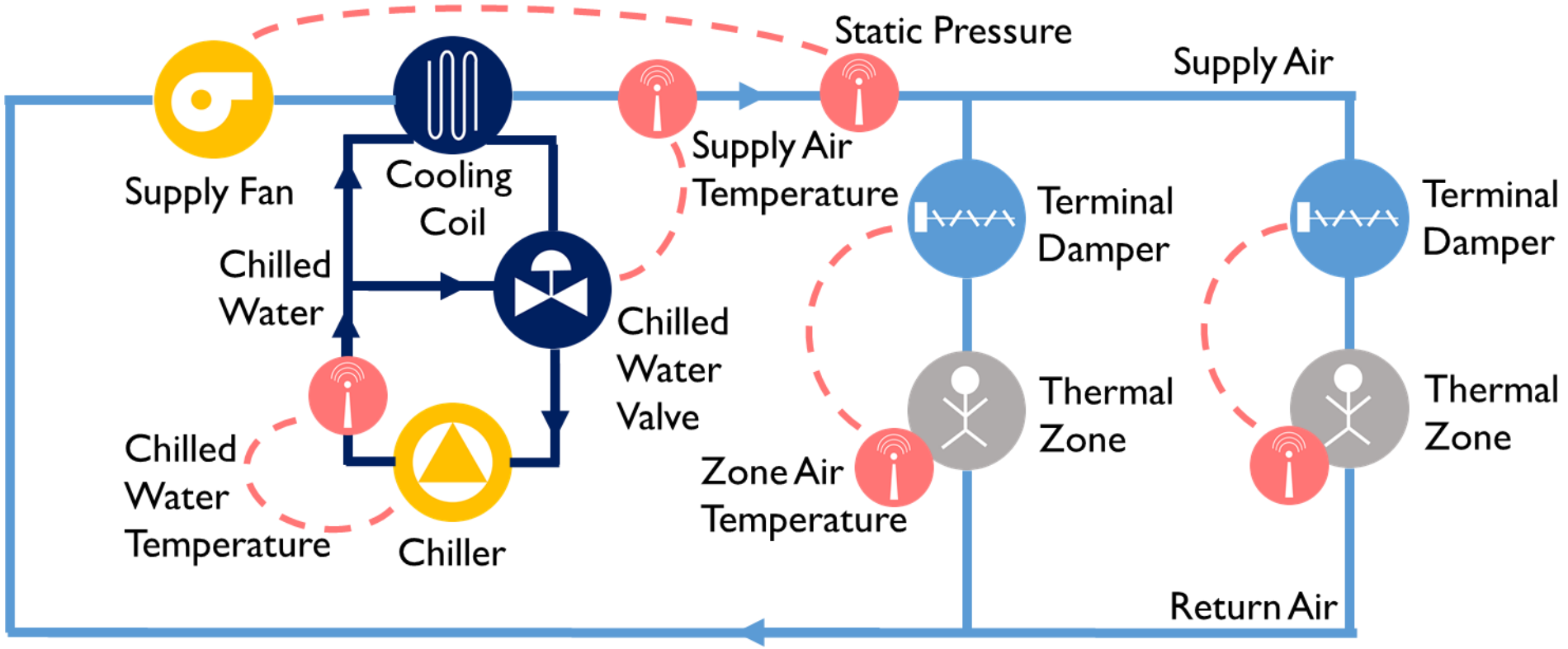
   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?

   Quick ASDR Resource Estimation

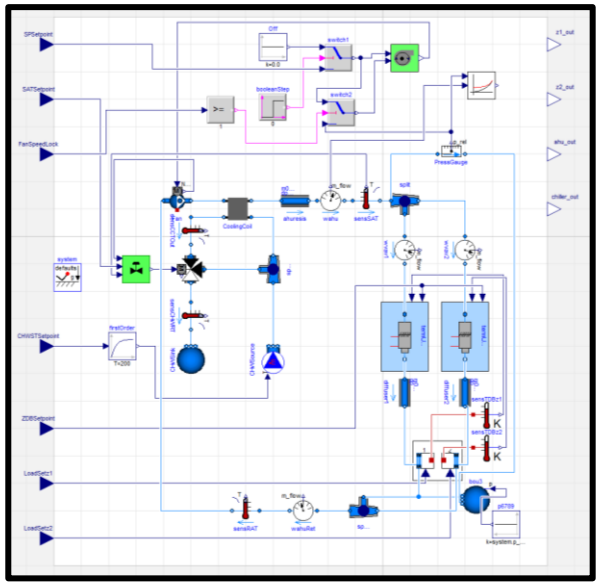
Goals

1) Consider a variable-air-volume (VAV) system
2) Analyze whole-system effects of providing reserve and regulation AS
3) Characterize successful and unsuccessful implementation strategies



Method

1) Construct dynamic system model using Modelica
2) Simulate reserve and regulation provision with various strategies and loading
3) Process data in MATLAB to identify trends



Strategies	Intensities	Load Conditions
Zone temperature	+/- 0 to 5 °C	Min to Design
Supply static pressure	+/- 0 to 80%	
Supply air temperature	+/- 0 to 5 °C	
Chilled water temperature	+/- 0 to 5 °C	

Summary

1) Most effective reserve provision required zone airflow change
2) Most effective regulation provision required direct control of fan and chiller
3) Symmetric regulation does not impact zone temperature
4) Modelica demonstrated to be most appropriate modeling tool for future AS control development

Future

1) Advanced AS control development
2) Role of Modelica

This section based on (Blum and Norford 2014a, 2014b)

Research Questions

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   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?

   Multi-market Optimization

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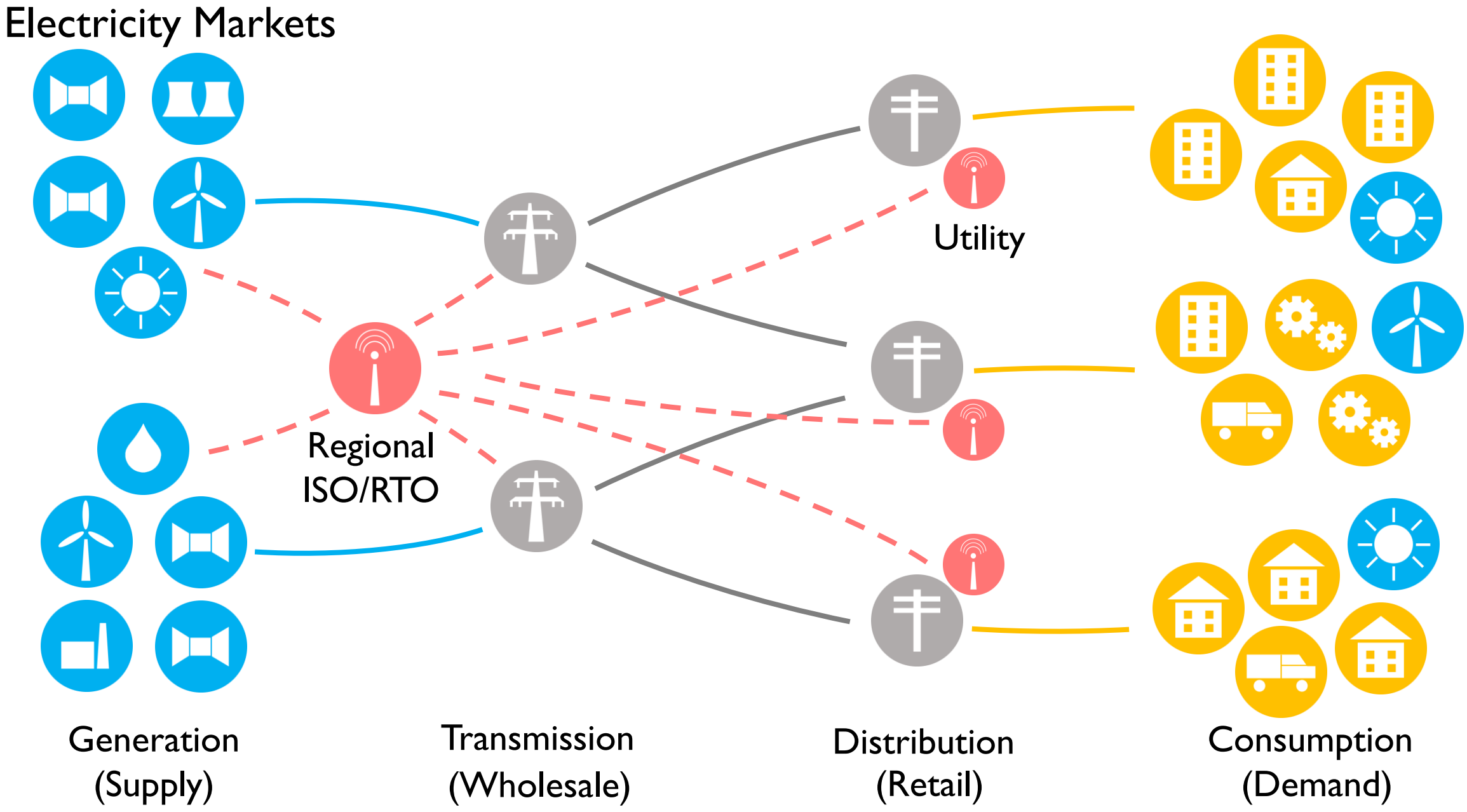
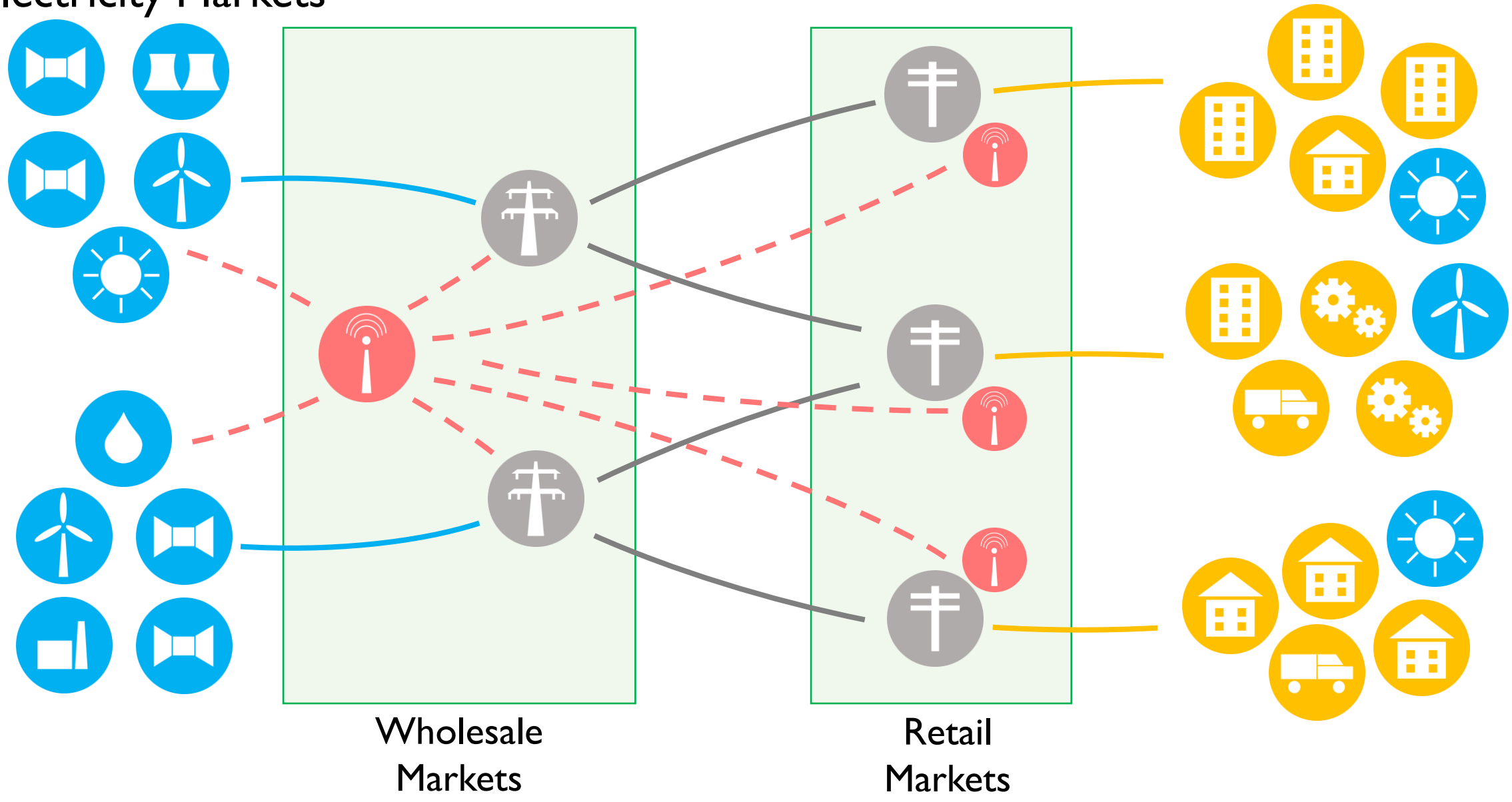
   Quick ASDR Resource Estimation

Multi-market Optimization

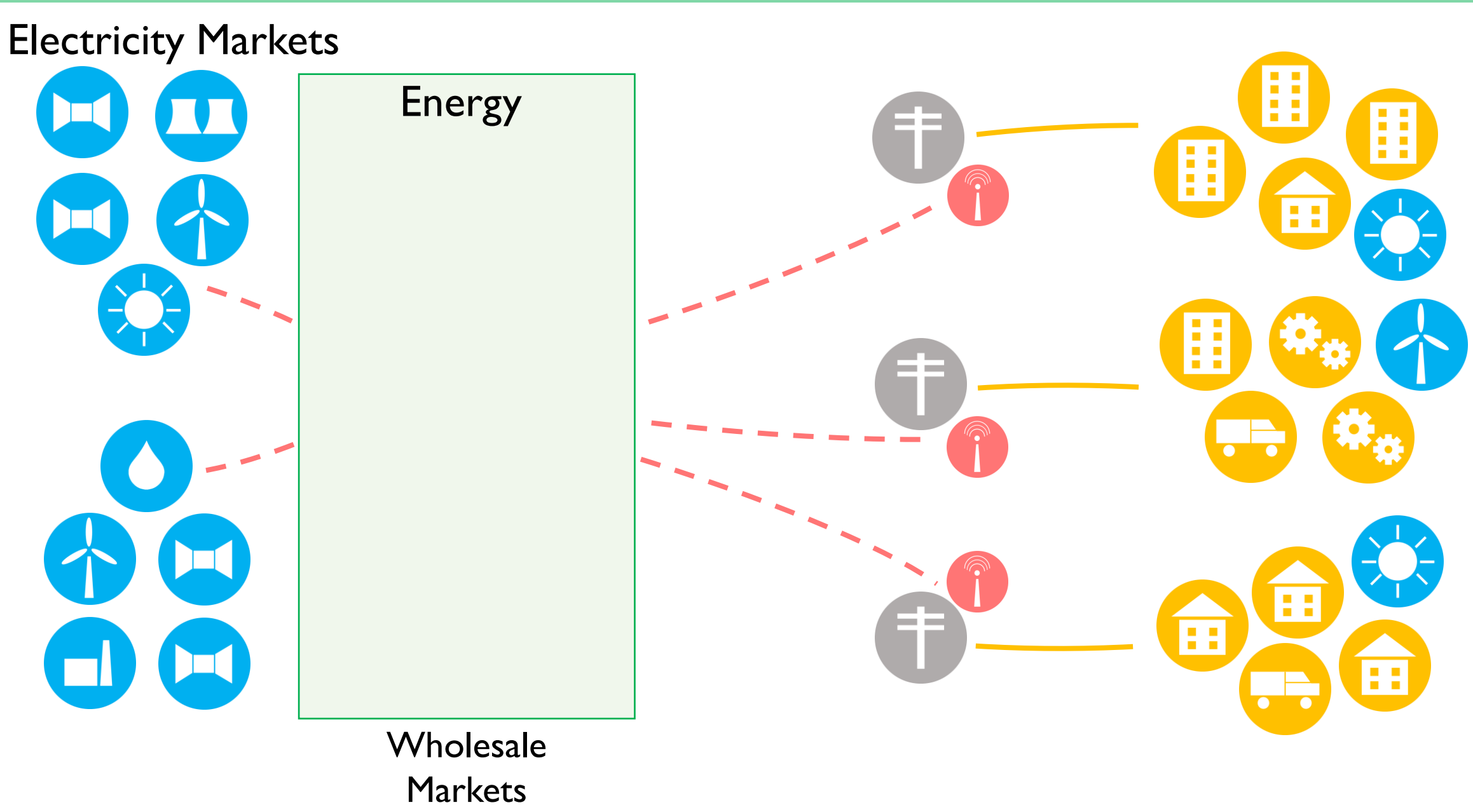


Multi-market Optimization

Electricity Markets

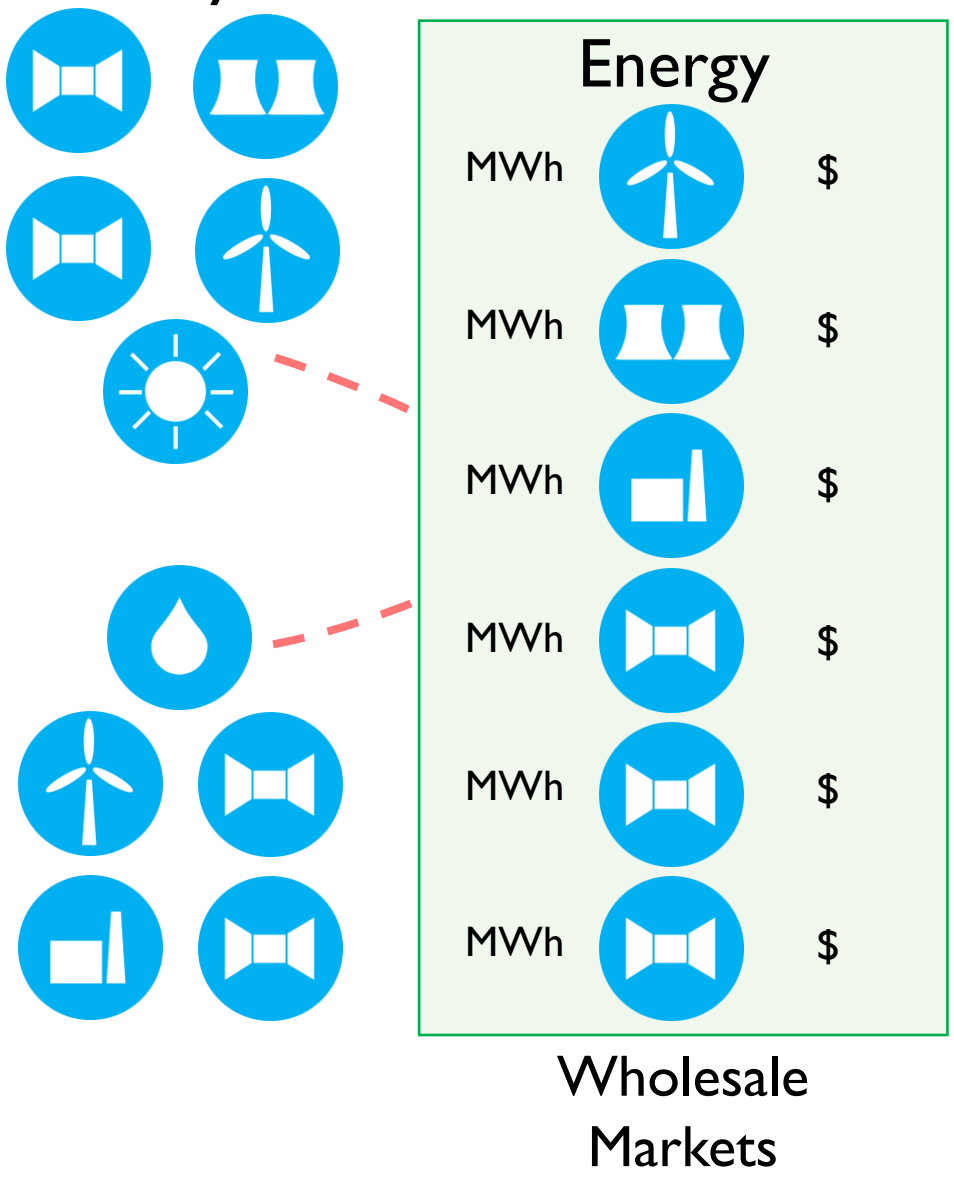


Multi-market Optimization



Multi-market Optimization

Electricity Markets

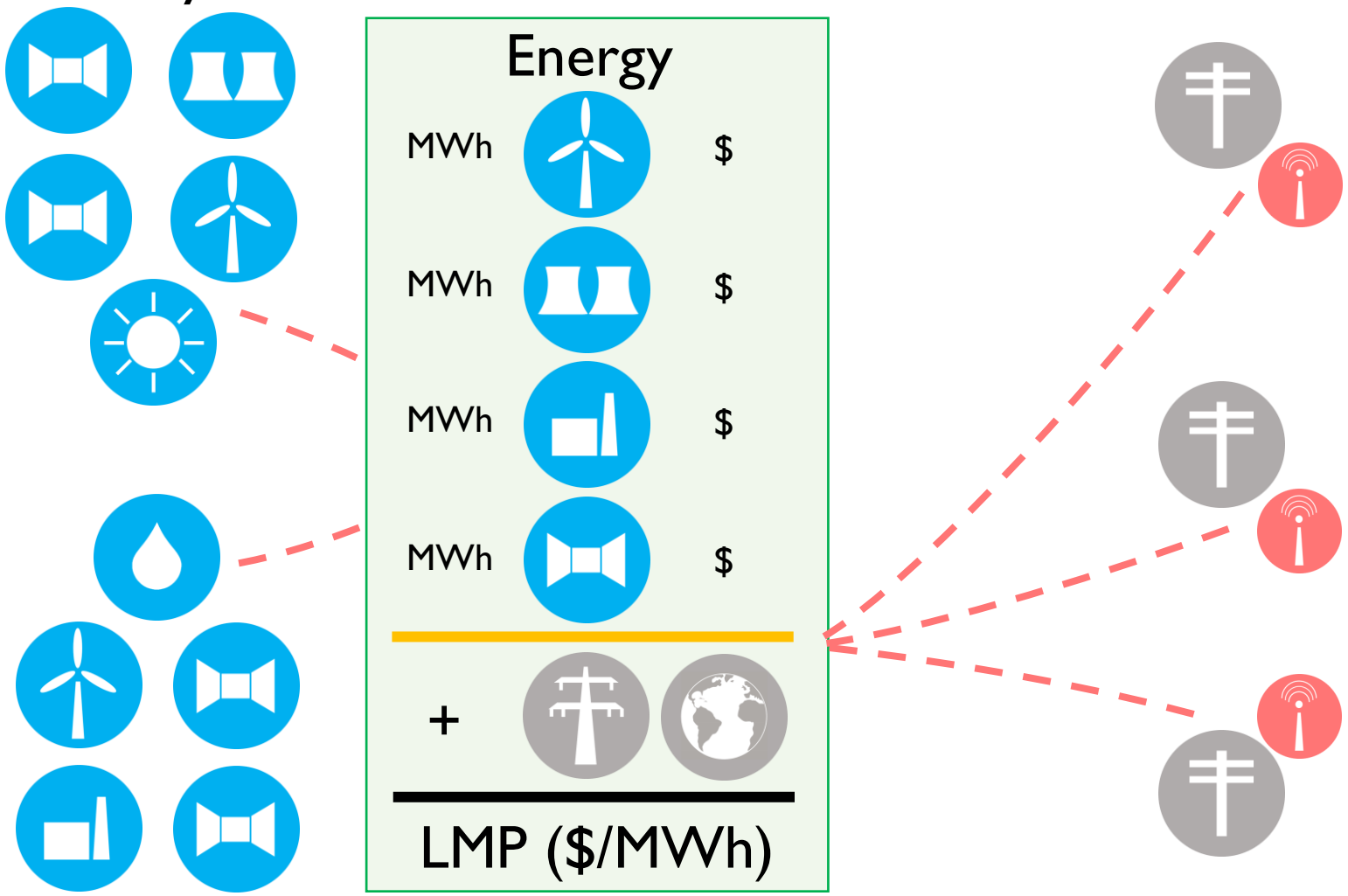


Day-Ahead (24 hour) looks ahead to next day

Real-Time (5 min) responds to current conditions

Multi-market Optimization

Electricity Markets



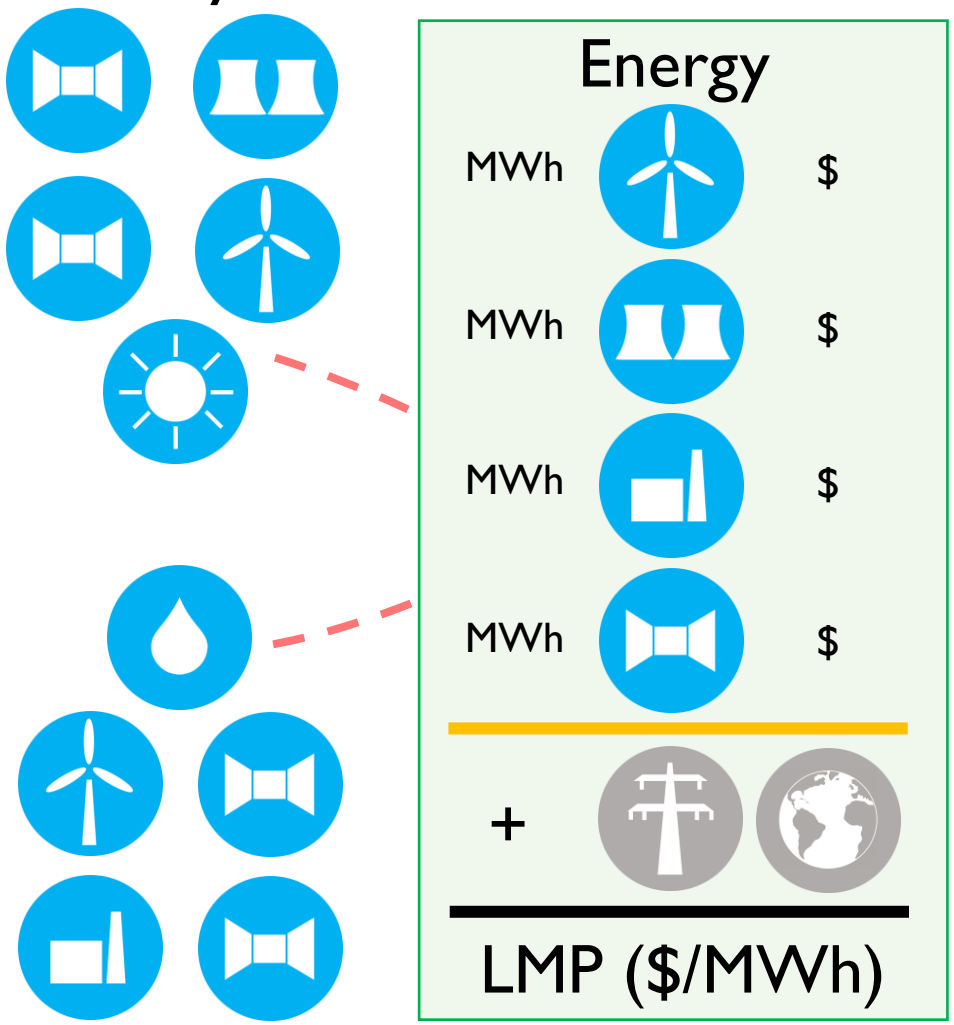
Wholesale Markets

All generators get paid the LMP

All load serving entities pay the LMP

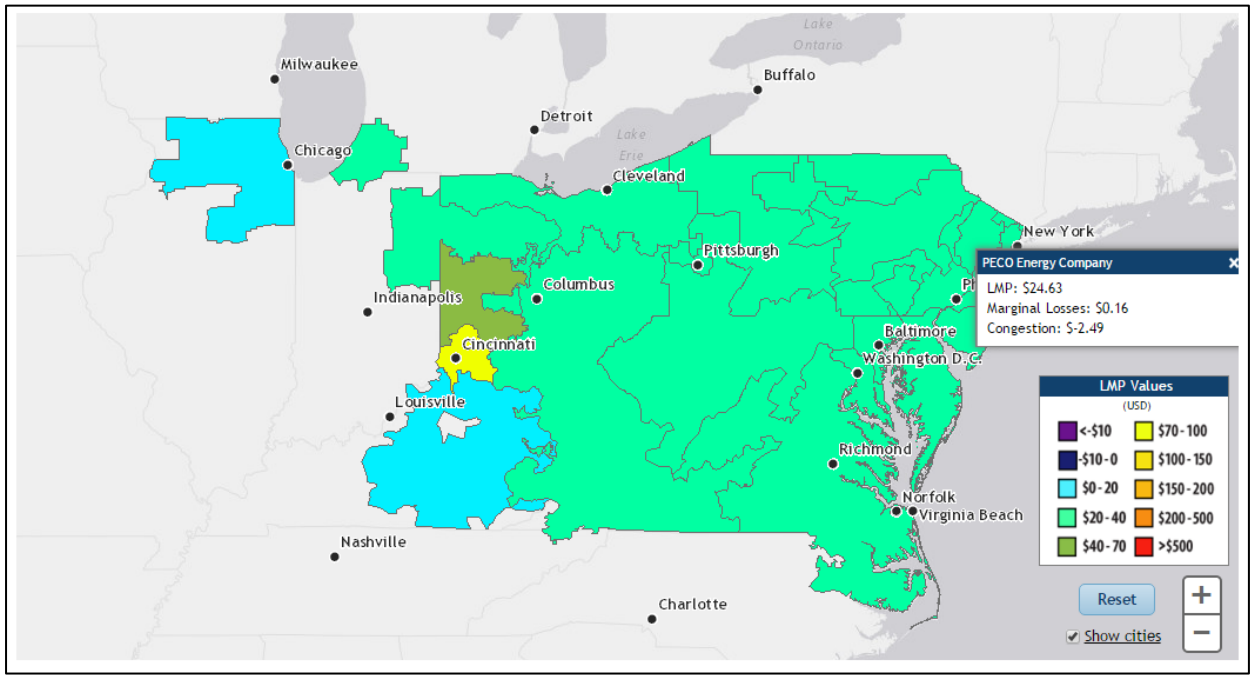
Multi-market Optimization

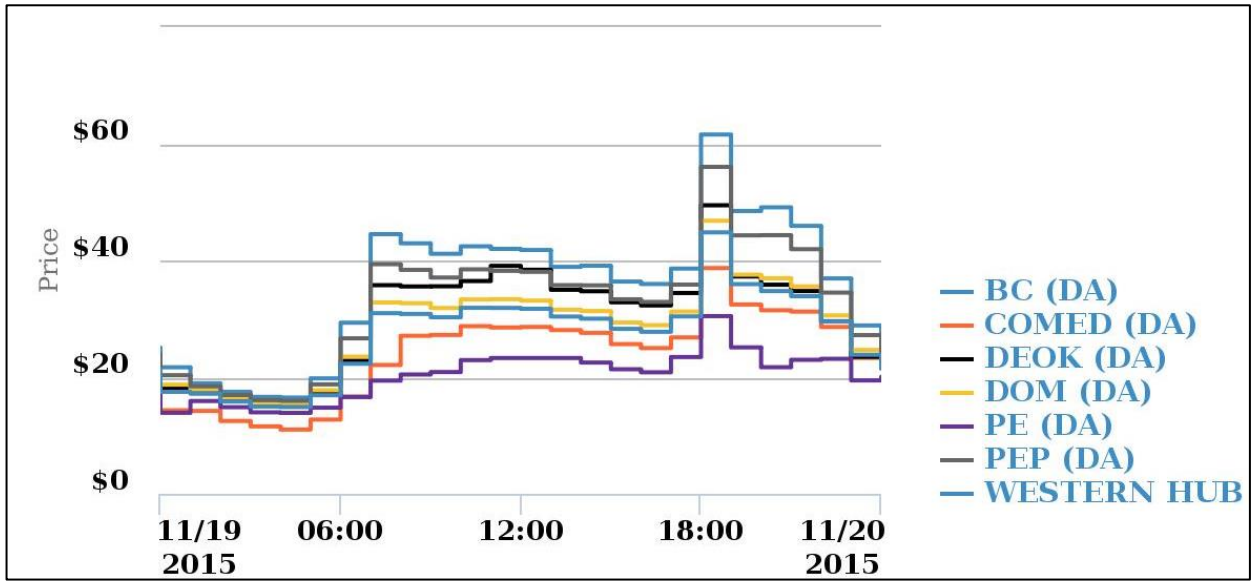
Electricity Markets



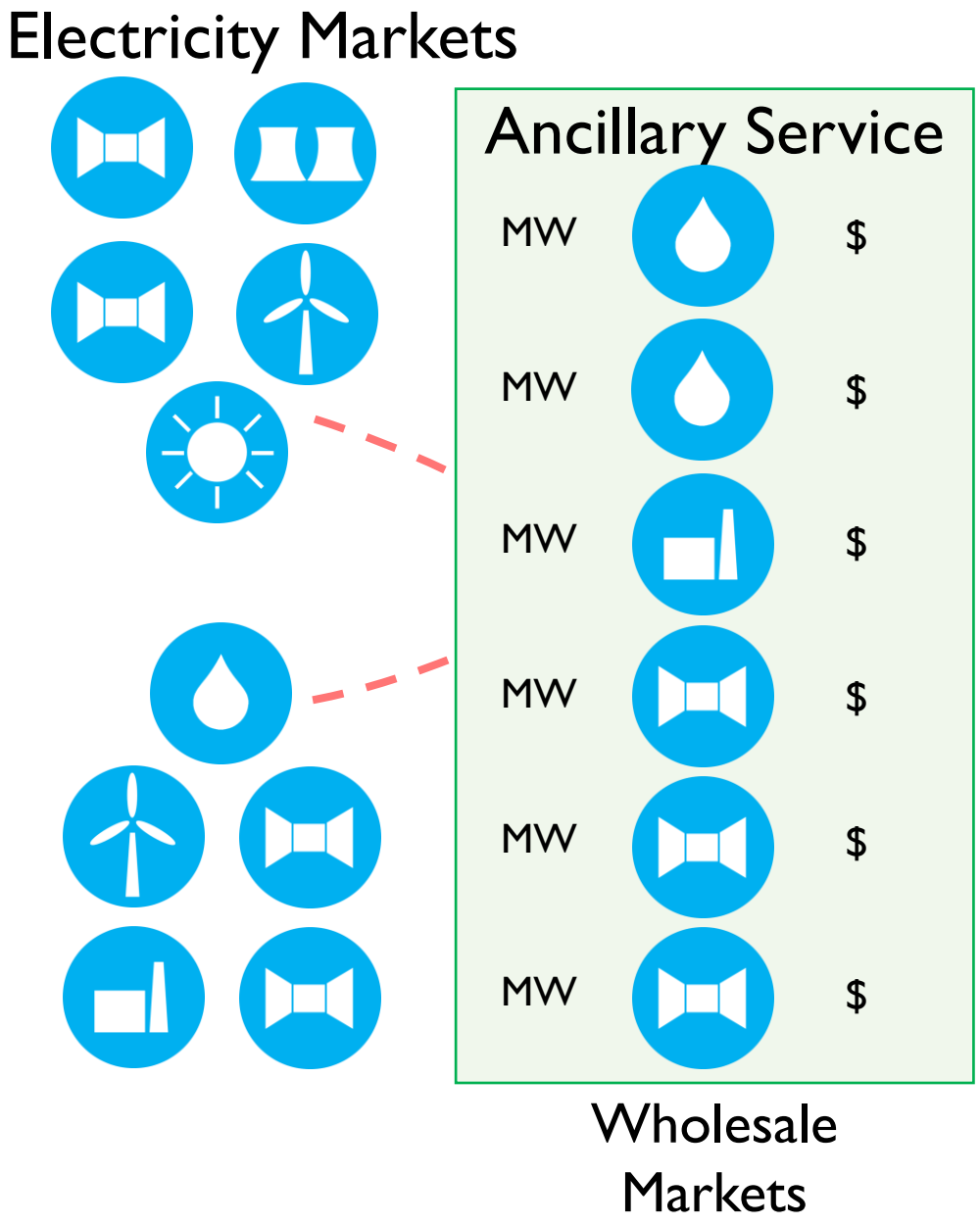
Wholesale Markets

(PJM 2016)



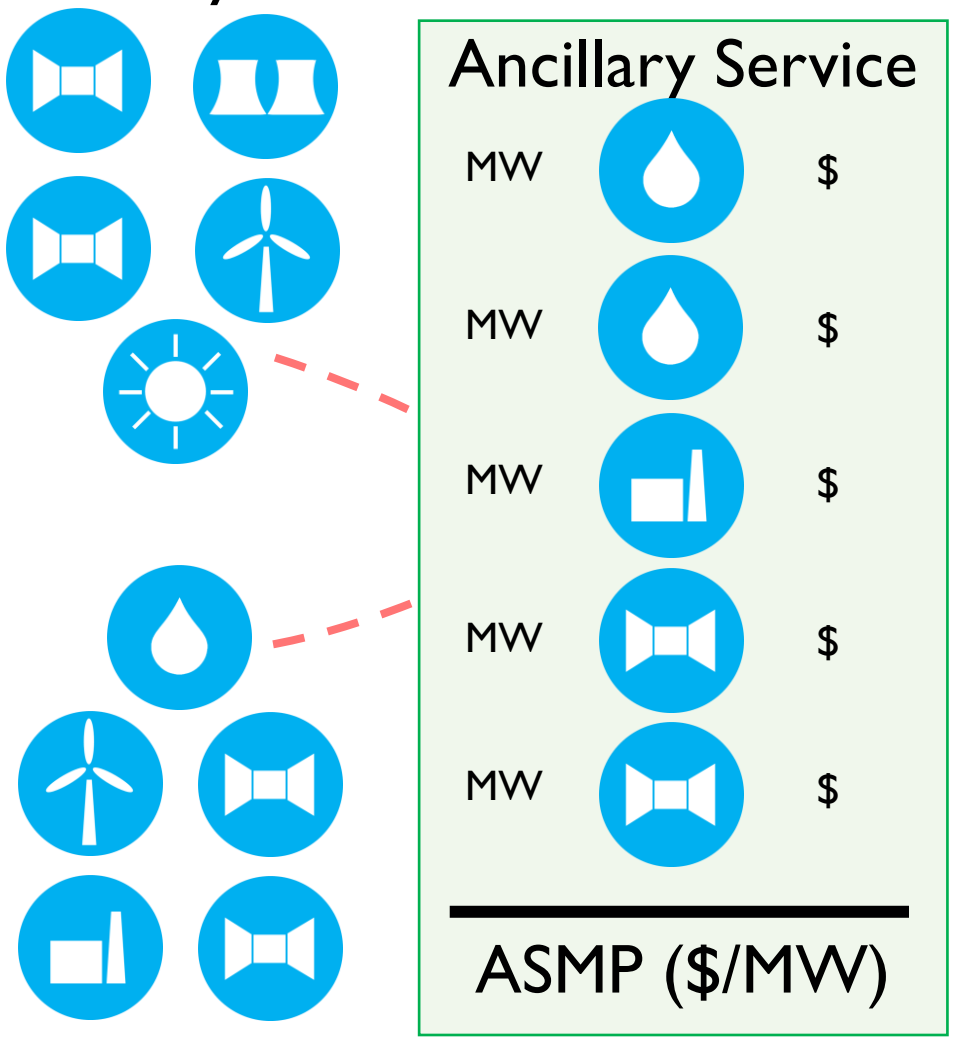


Multi-market Optimization



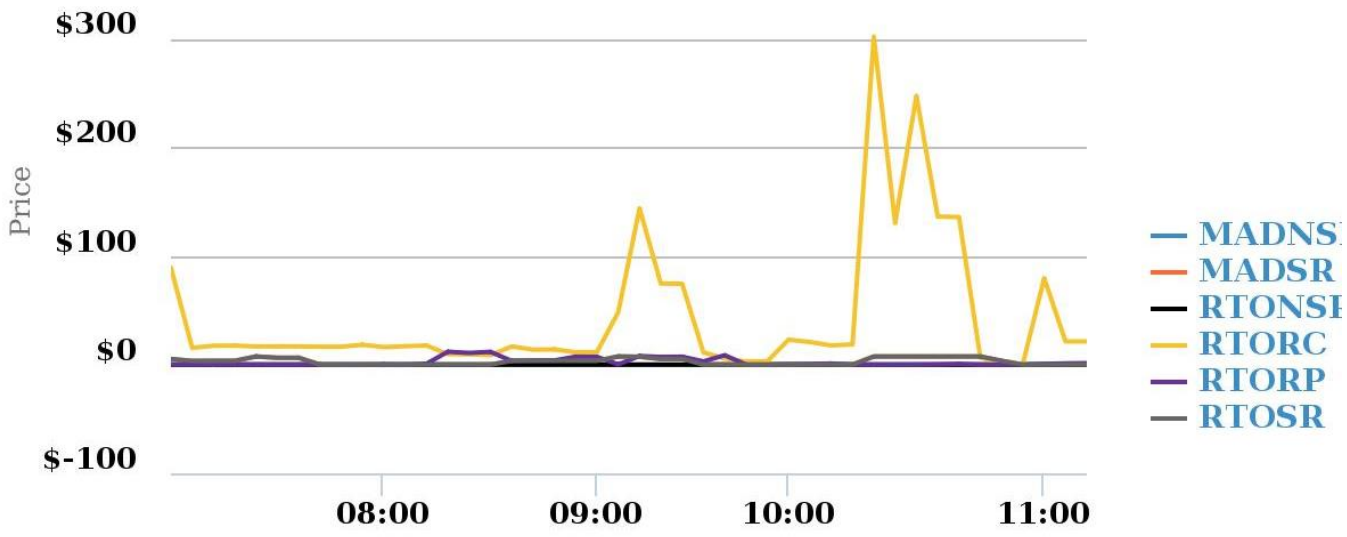
Multi-market Optimization

Electricity Markets



Wholesale Markets

All generators providing AS get paid the ASMP

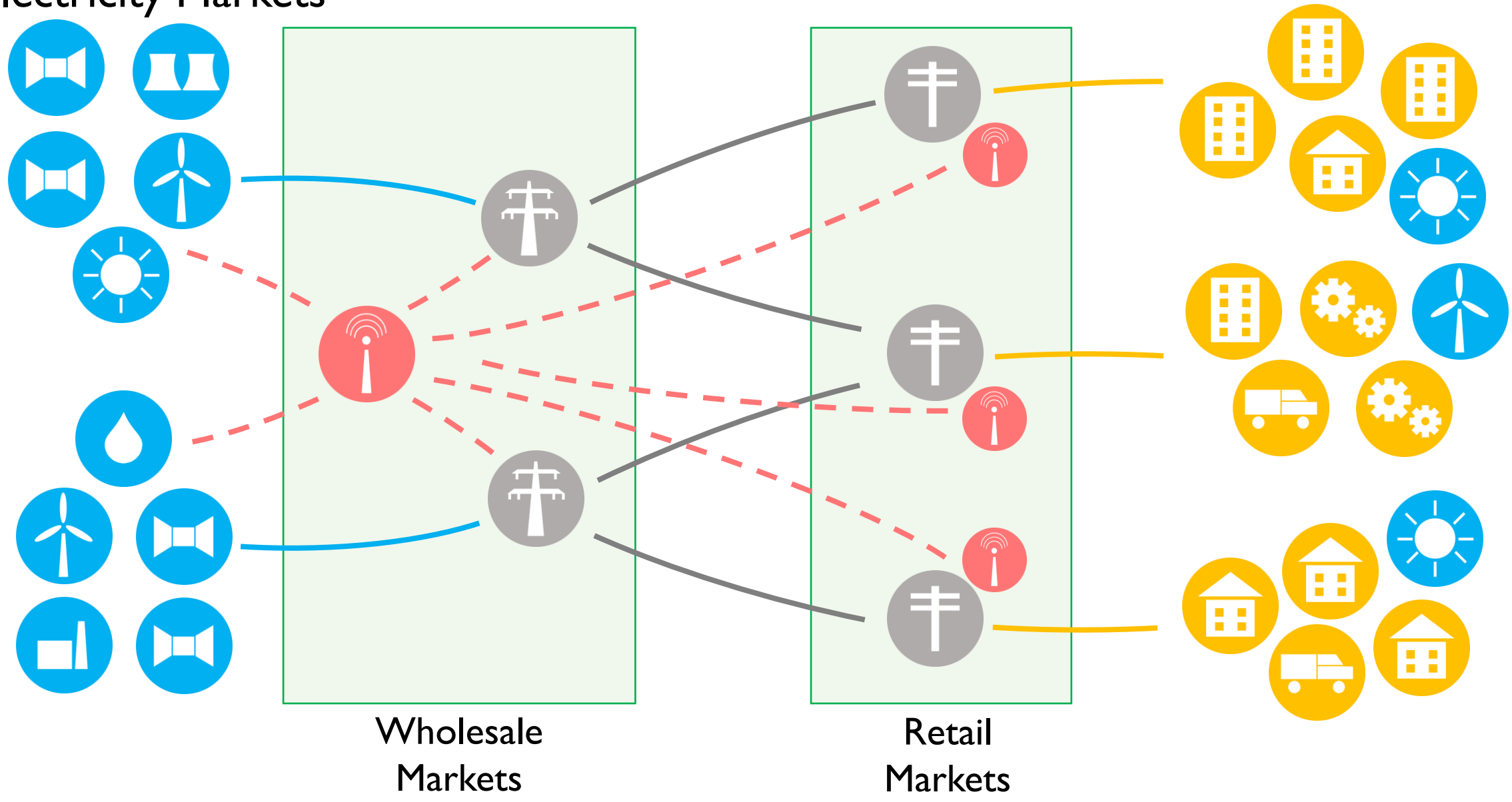


(PJM 2016)

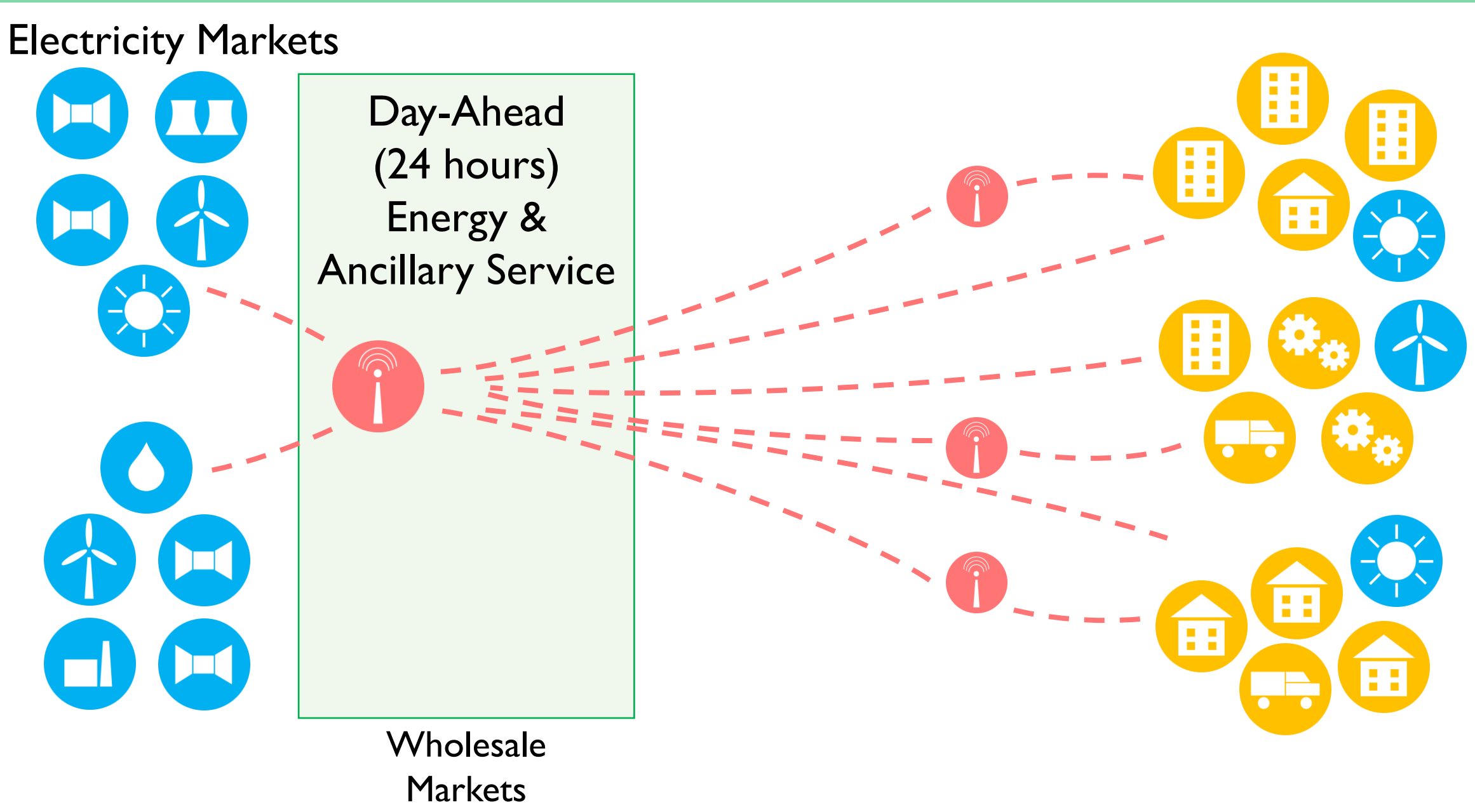
Reliability Standards

Multi-market Optimization

Electricity Markets



Multi-market Optimization



MPC Literature

Concentrate on multi-zone VAV systems and multi-market Optimization

Energy or Energy Price Optimization (E-market)

Li et al. 2015	– 2 hour planning horizon
Henze et al. 2004	– 24 hour planning horizon, 4 decision periods
Greensfelder et al. 2011	– 24 hour planning horizon, 6 decision periods

Multi-market Optimization

Vrettos et al. 2014	– 48 hour planning horizon, LMP + Regulation pricing (EL-market) – aggregator of independent single-zone buildings
Pavlak et al. 2014	– 24 hour planning horizon, LMP + Regulation pricing (EL-market) – VAV systems approximated as single-zone – perturbation approach, optimization time ~ 1-6 hours on 12-core CPU

Multi-market Optimization

Goals

1) Formulate multi-zone VAV system 24-hour multi-market (ELR) optimization
2) Solve 24-hour E-market optimization and improve optimization time
3) Solve 24-hour ELR-market optimization

Method

1) Formulate ELR-market optimization problem

Minimize: Daily (Energy Cost – Regulation Revenue – Reserve Revenue)

Subject to:

- Zone Temperature physics
- Zone Thermal Comfort
- Zone Heat/Cool Limits
- System Capacity Limits

} Primary Problem

- Dispatched Reserve Zone Temperature physics
- Dispatched Reserve Zone Thermal Comfort
- Dispatched Reserve Zone Heat/Cool Limits

} Secondary Problem

And calculate:

- HVAC Energy
- Dispatched Reserve HVAC Energy
- Regulation Capacity
- Reserve Capacity

Method

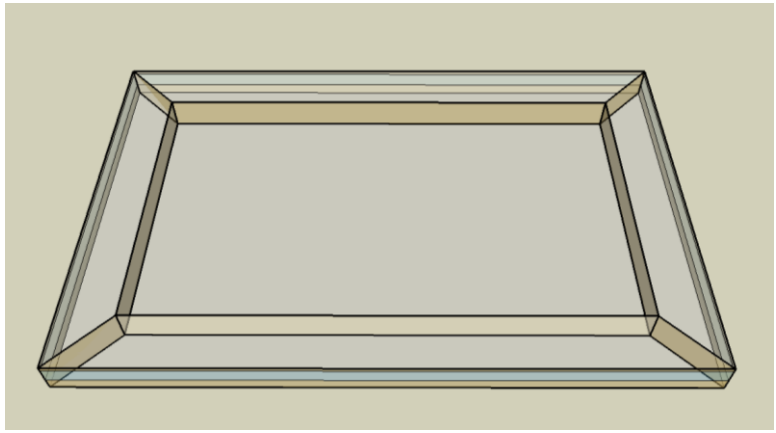
1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model

Multi-zone iCRTF *(Armstrong et al. 2006, Gayeski 2011)*

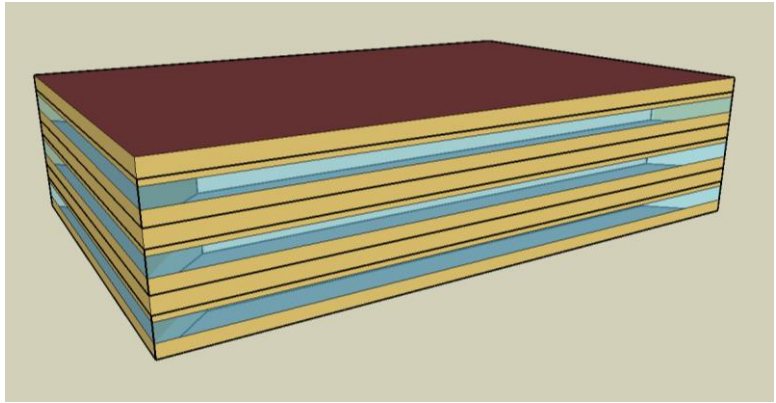
<u>Linear combination of current and past:</u>
Zone temperatures
Zone HVAC heat rates
Adjacent zone temperatures
Exogenous load variables

DOE Commercial Reference Buildings

6-Zone



18-Zone



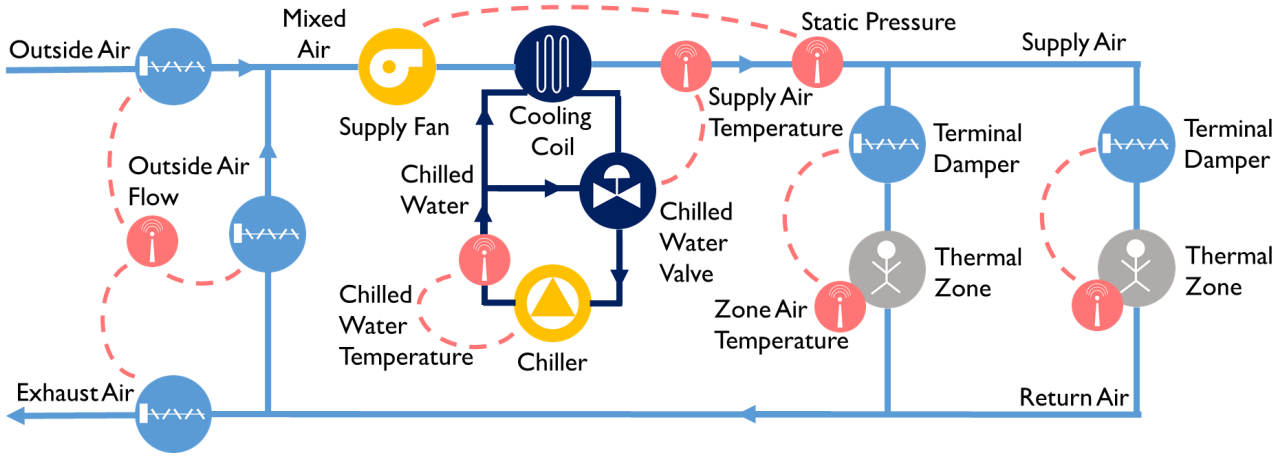
Multi-market Optimization

Method

1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model
3) Develop multi-zone VAV system model

Previously established models for:

Zone airflow	(Energy balance)
Supply fan airflow	(Mass Balance)
Return air temperature	(Energy balance)
Mixed air temperature	(Energy balance)
Coil cooling load	(Energy balance)
Chiller power	(E+ EIR Chiller)
Fan power	(VSD SP Control Fan)
Total HVAC power	*(Englander and Norford 1992)*



Multi-market Optimization

Method

1) Formulate ELR-market optimization problem
2) Develop zone temperature physics model
3) Develop multi-zone VAV system model
4) Implement and solve in MATLAB

Computer:

Windows 7 x64
2-core Intel® Core™ i5-4200U CPU, 2.30 GHz
8 GB Physical RAM
MATLAB 2013a x86

Solver:

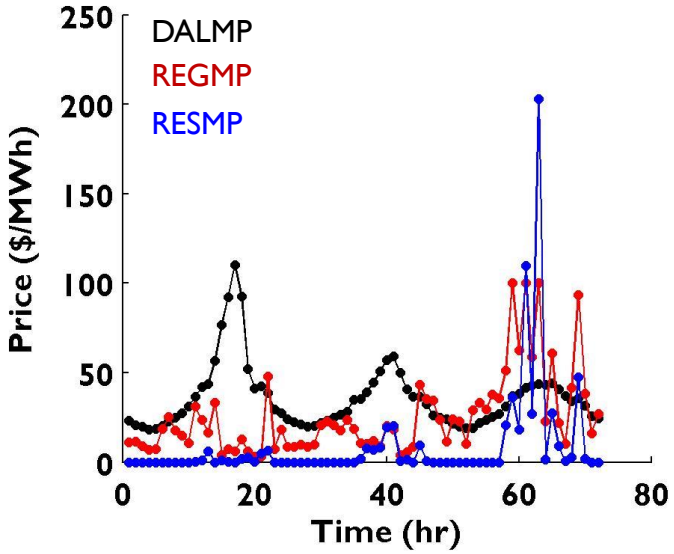
Fmincon w/ Sequential Quadratic Programming (SQP)

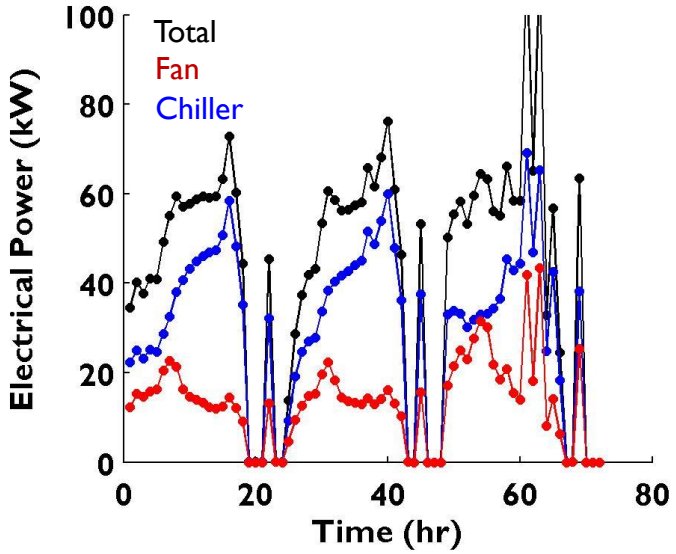
24-Hour Optimization Time:

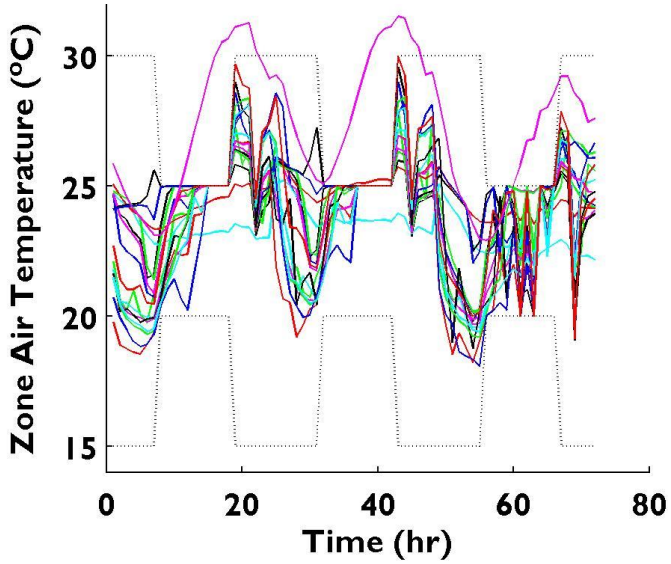
E-market:	5-zone ~ 30 s, 18-zone ~ 5-20 min
ELR-market:	5-zone ~ 2-6 min 18-zone ~ 1-4 hours

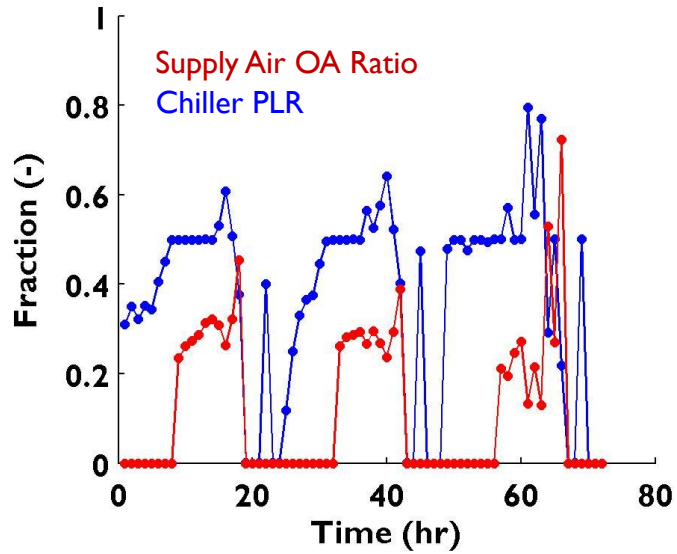
D. H. Blum, N. Xu, and L. K. Norford (2016), "A novel multi-market optimization problem for commercial HVAC systems providing ancillary services using multi-zone inverse comprehensive room transfer functions." Science and Technology for the Built Environment, Topical Issue Smart Grid and Buildings, in review.

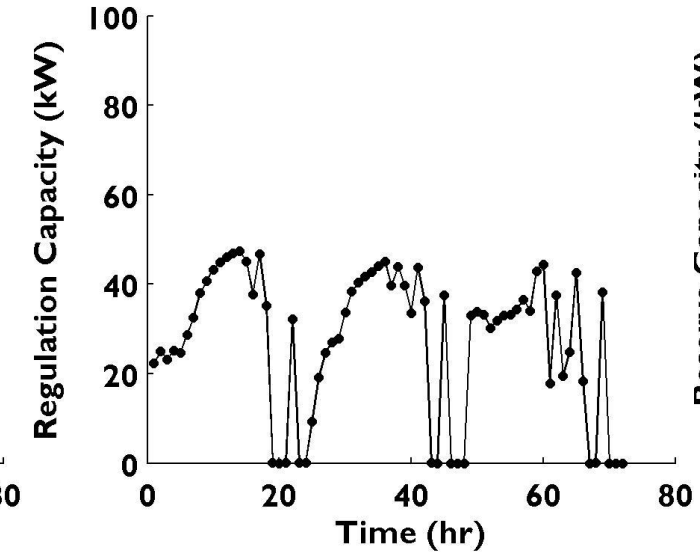
Results – ELR-market Optimization, 18-zone

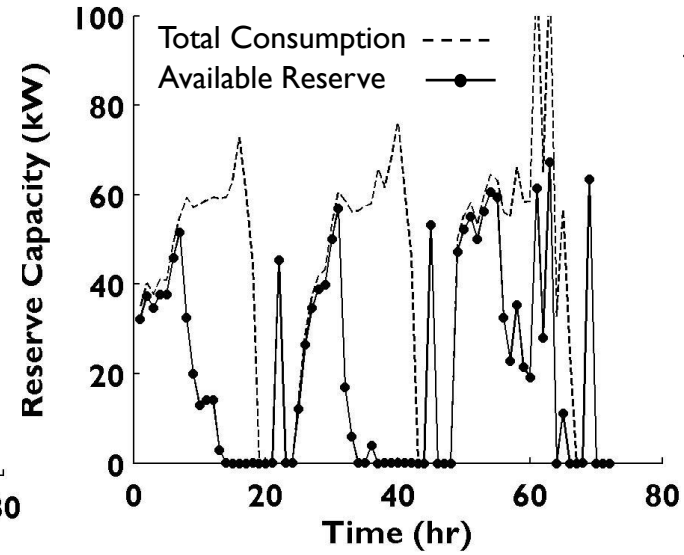












3-Day Operating Costs:

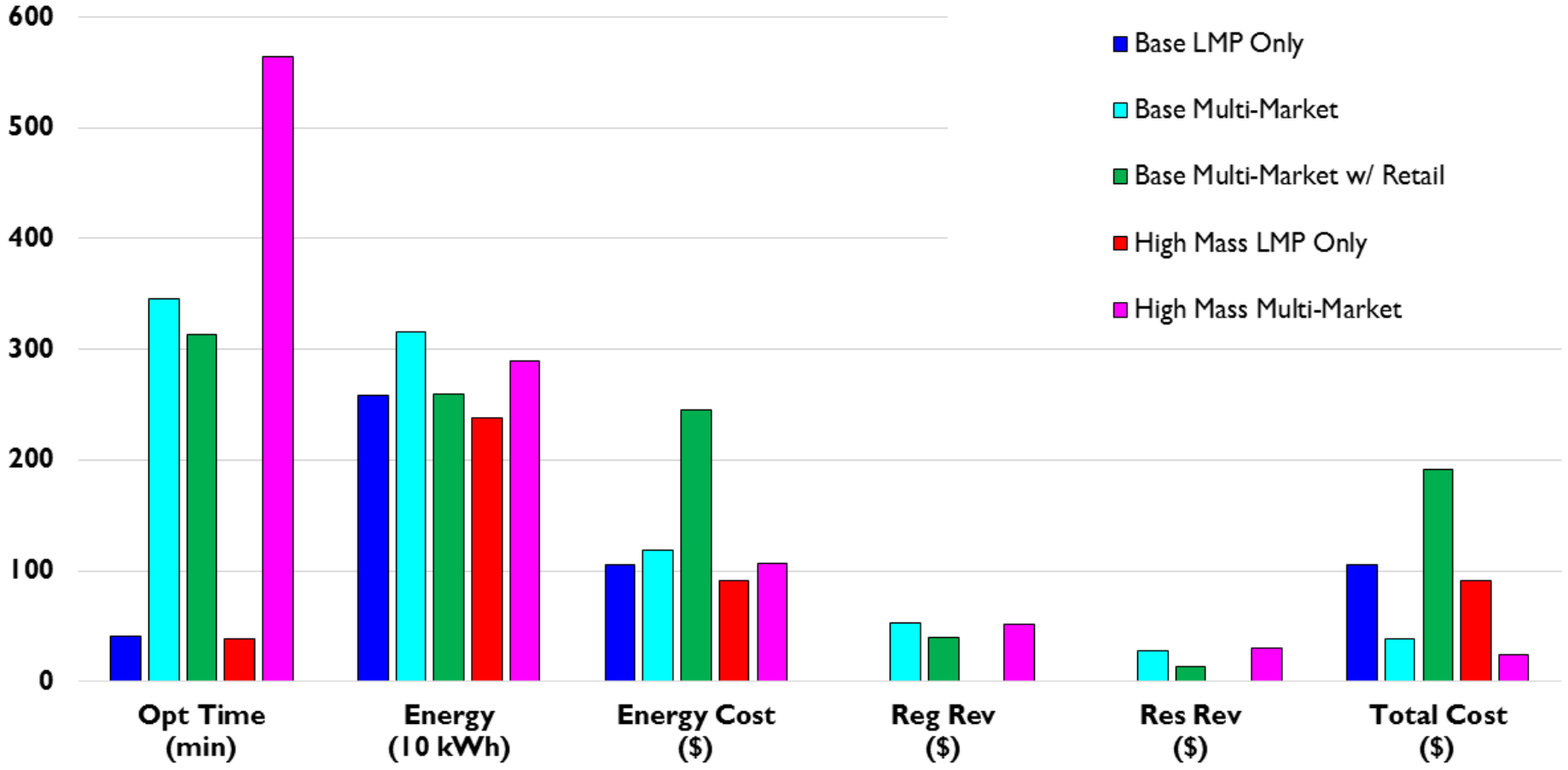
Energy: $118.57

Regulation: -$52.52

Reserve: -$27.21

D. H. Blum, N. Xu, and L. K. Norford (2016), "A novel multi-market optimization problem for commercial HVAC systems providing ancillary services using multi-zone inverse comprehensive room transfer functions." Science and Technology for the Built Environment, Topical Issue Smart Grid and Buildings, in review.

Results – ELR-market Optimization, 18-zone



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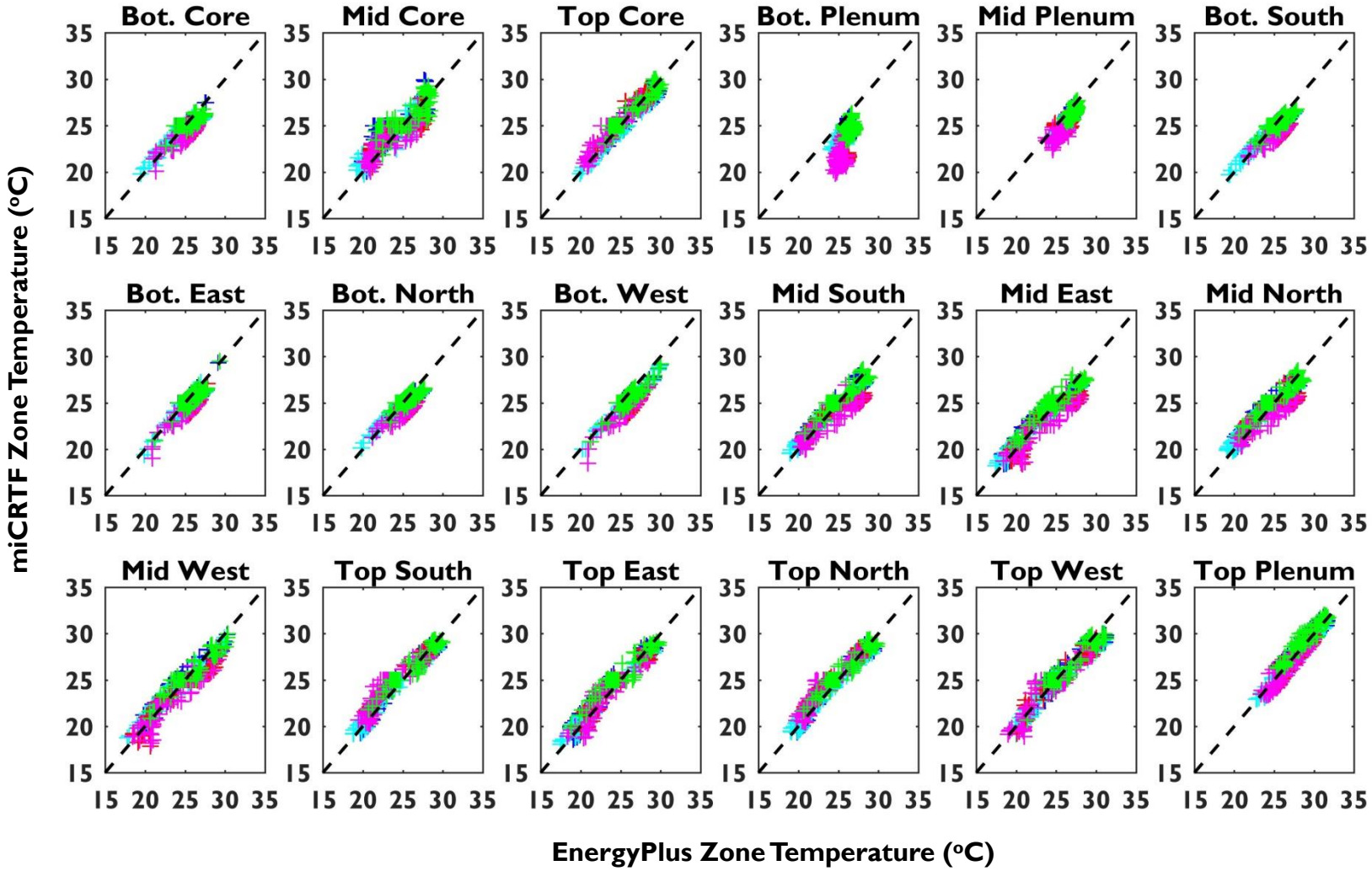

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Multi-market Optimization

Summary

1) Successful 24-hour ELR-market optimization for 18-zone VAV system
2) HVAC systems can be incentivized to provide a portfolio of services with exposure to ancillary service market prices
3) Relatively high retail prices limit the incentives provided by wholesale market prices

Future

1) Latent energy
2) Regulation limit determination
3) Experimental implementation and validation

This section based on (Blum et al. 2016a)

Research Questions

1) How do HVAC systems provide ancillary services?

   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?

   Multi-market Optimization

3) Is there a price for providing ancillary services?

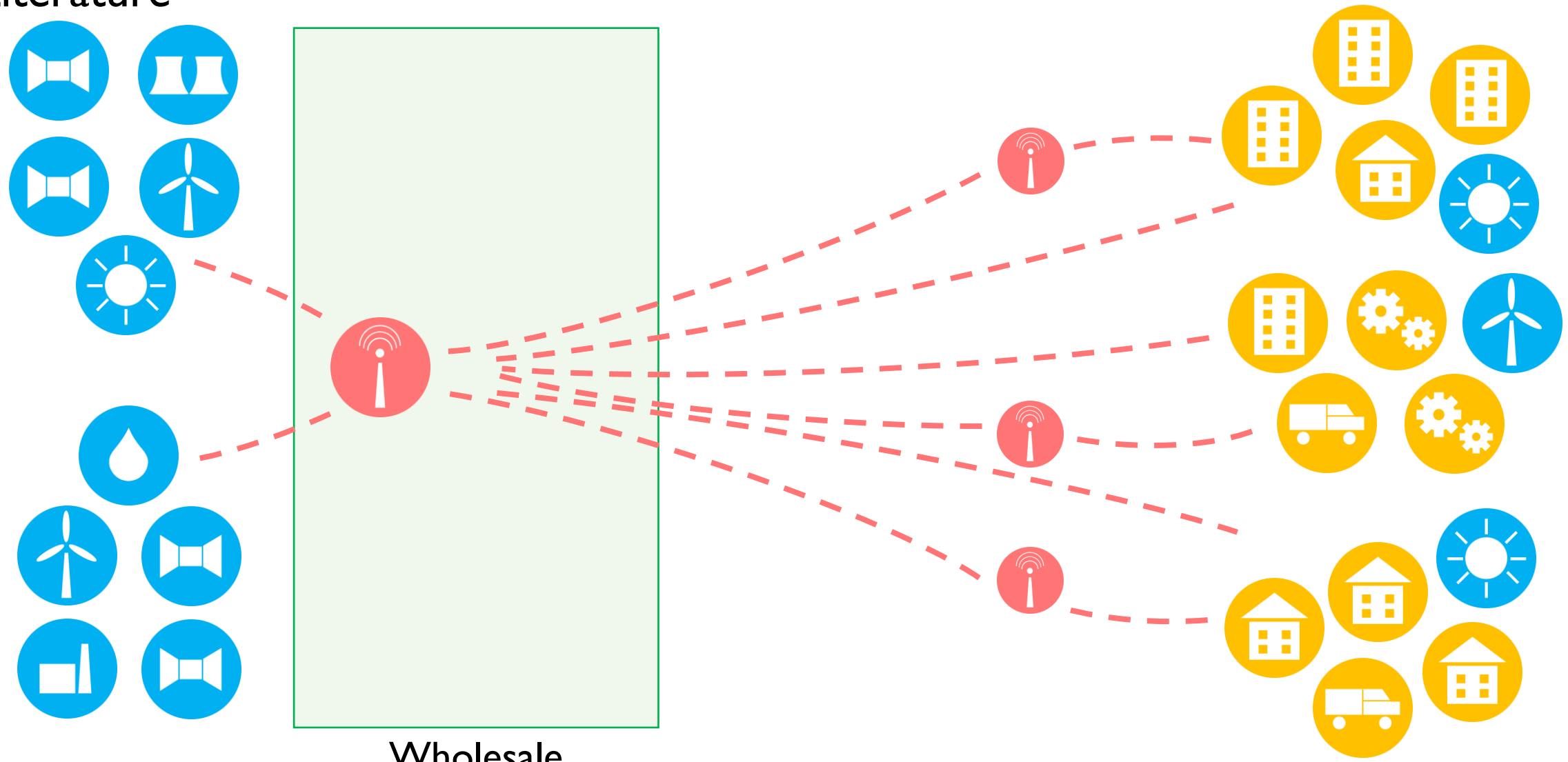
   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?

   Quick ASDR Resource Estimation

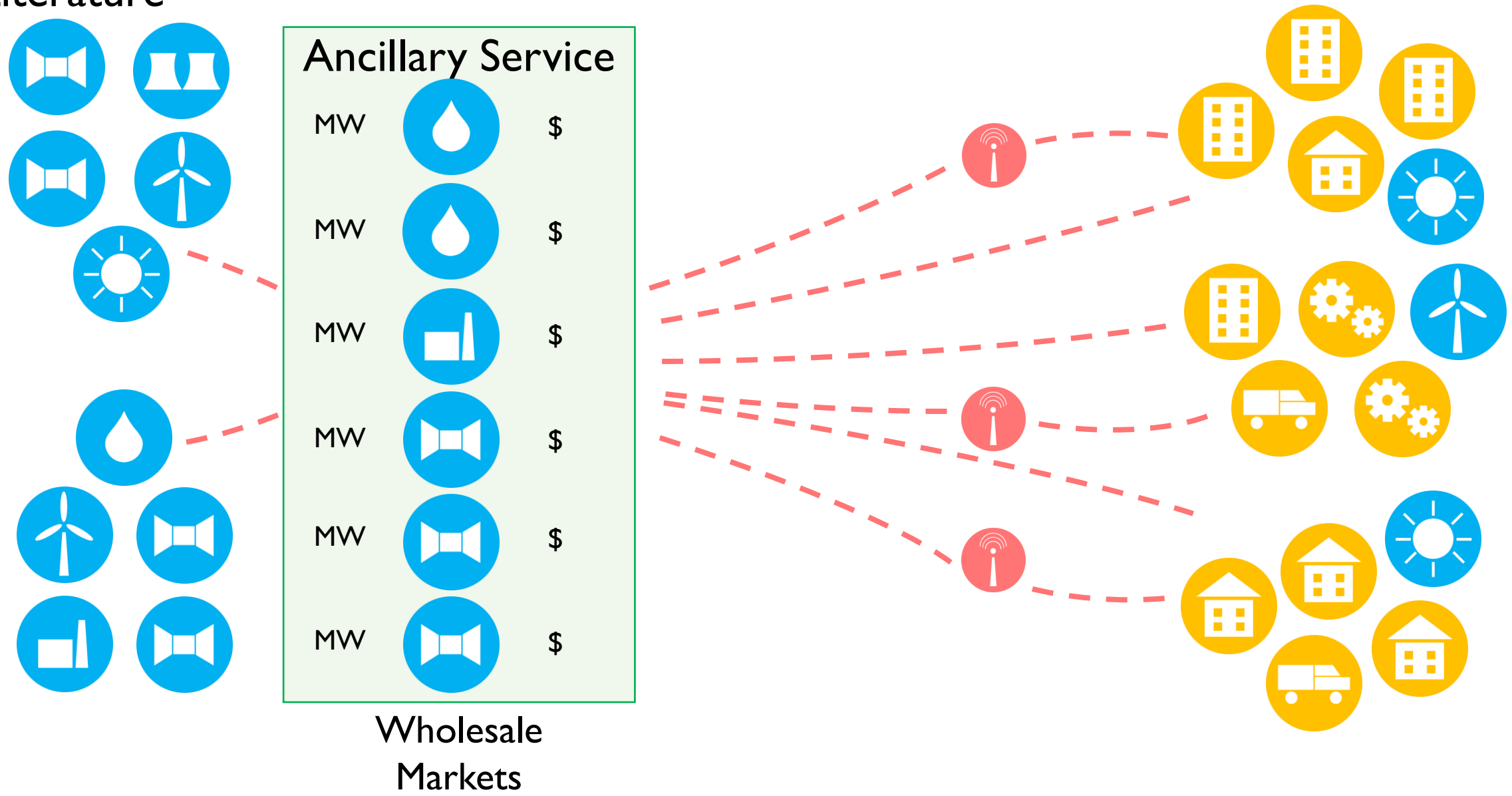
Opportunity Cost Quantification

Literature



Opportunity Cost Quantification

Literature



Opportunity Cost Quantification

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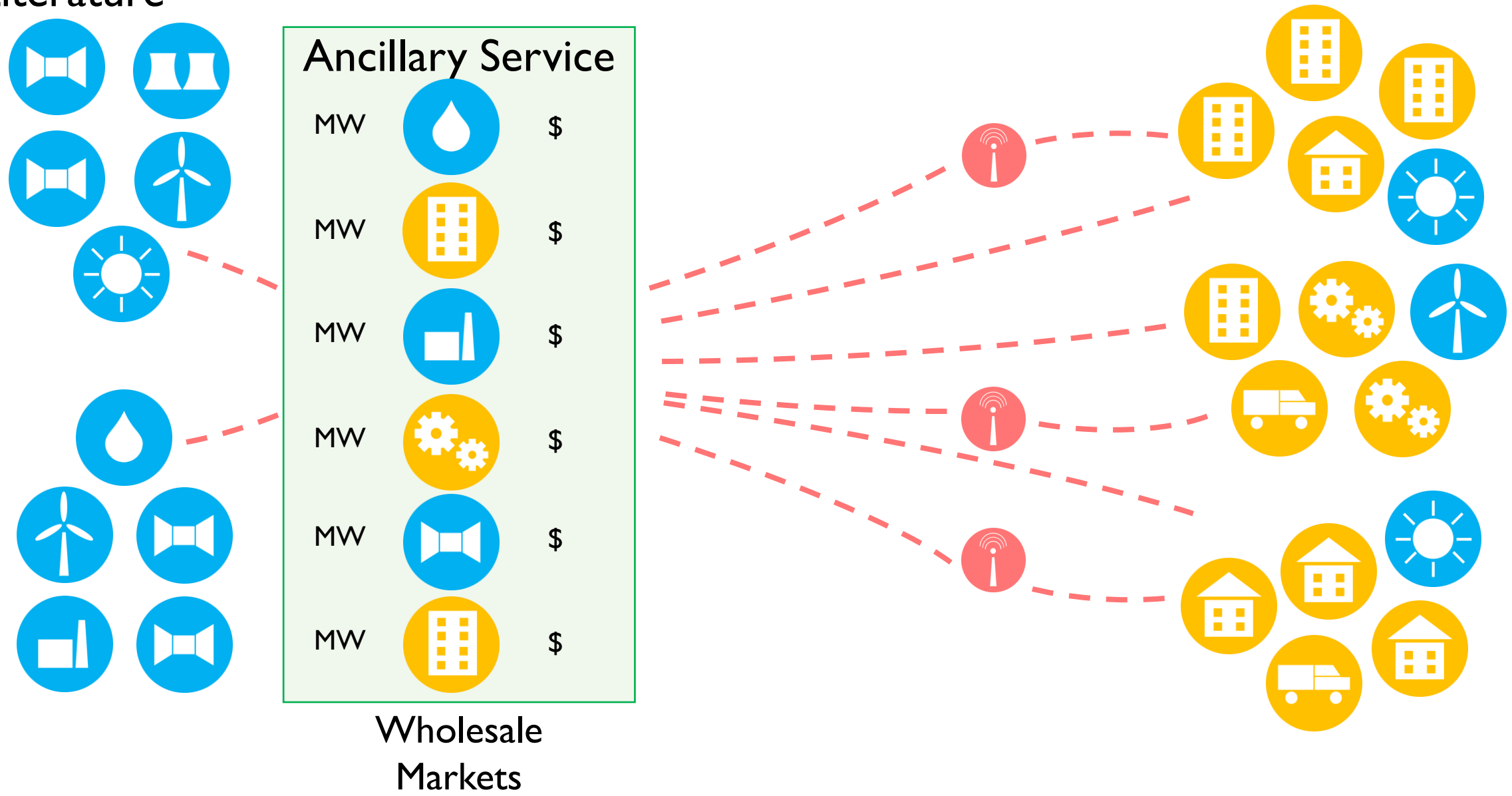
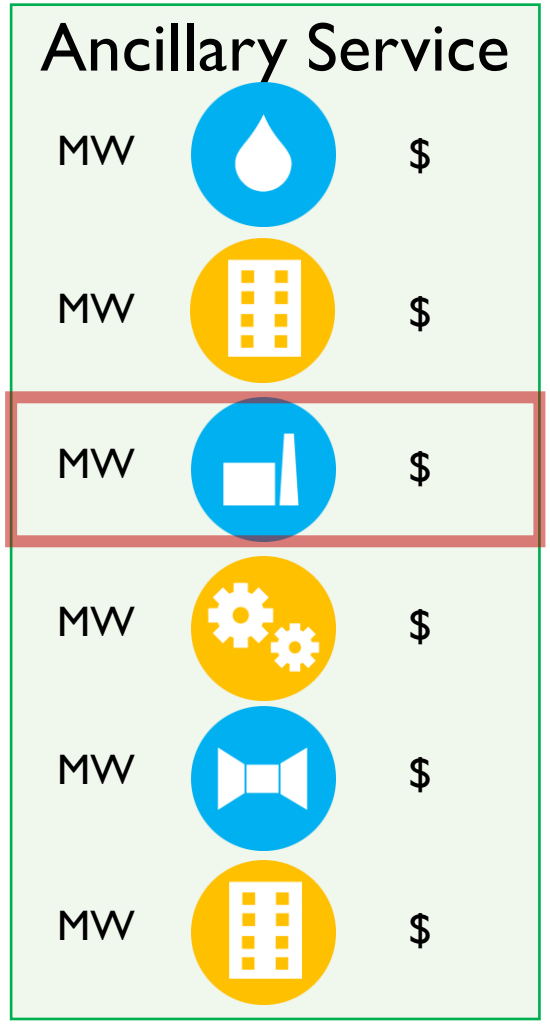


Opportunity Cost Quantification

Opportunity Costs



Wholesale Markets

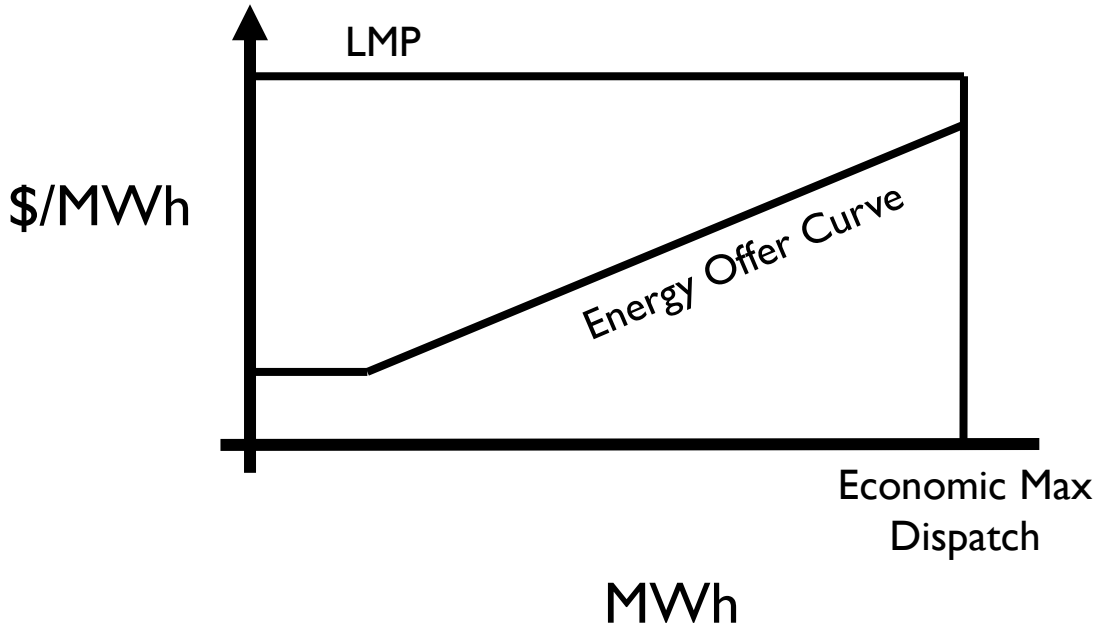
(65-75% Hummon et al. 2013)

Offer Cost = Operating Cost + Lost Opportunity Cost

Additional fuel and efficiency loss

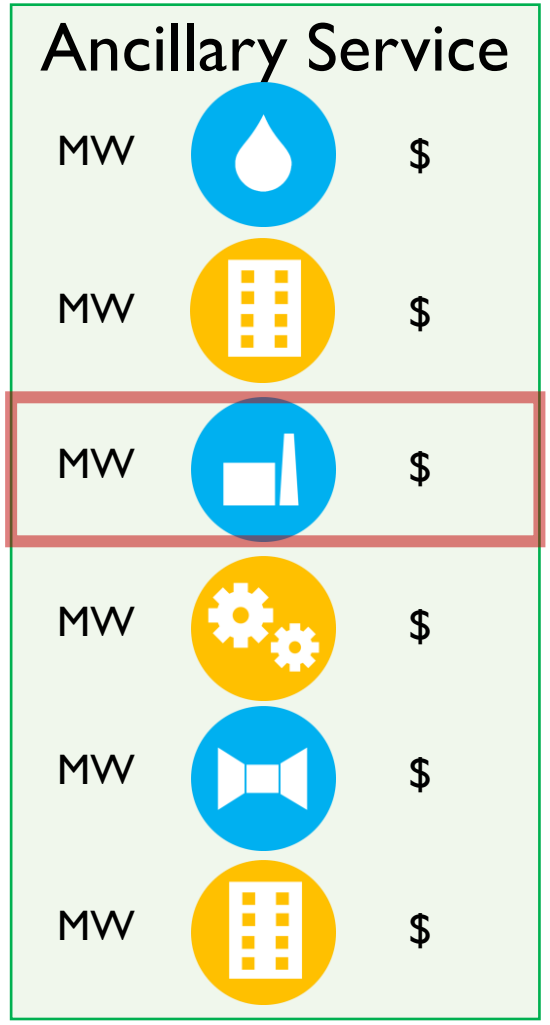
Forgone profit from energy market

(FERC Order 755)



Opportunity Cost Quantification

Opportunity Costs



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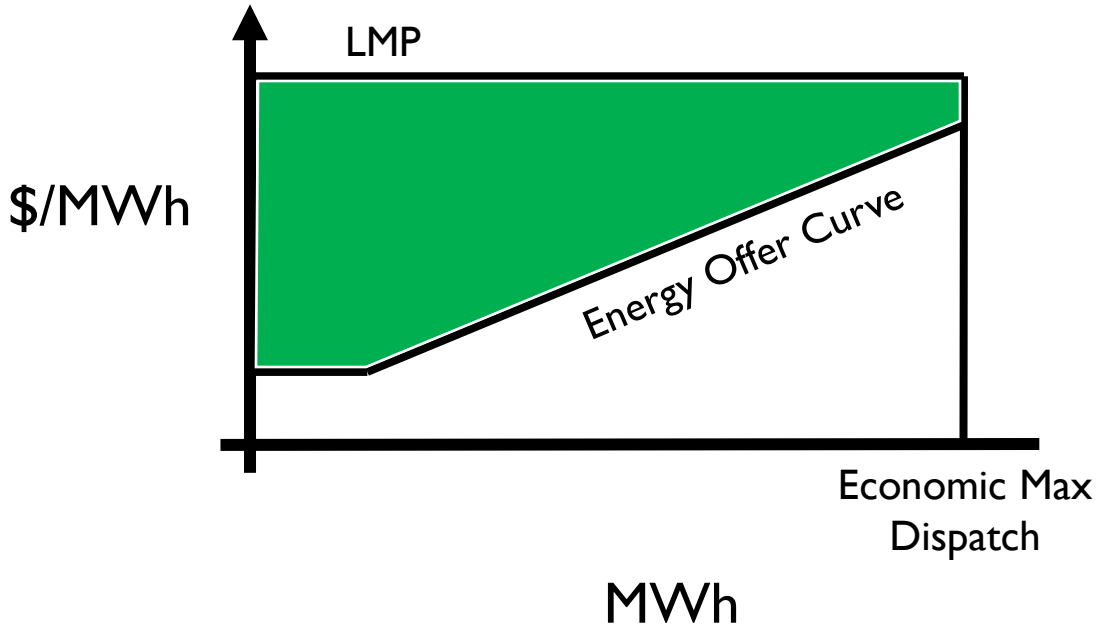
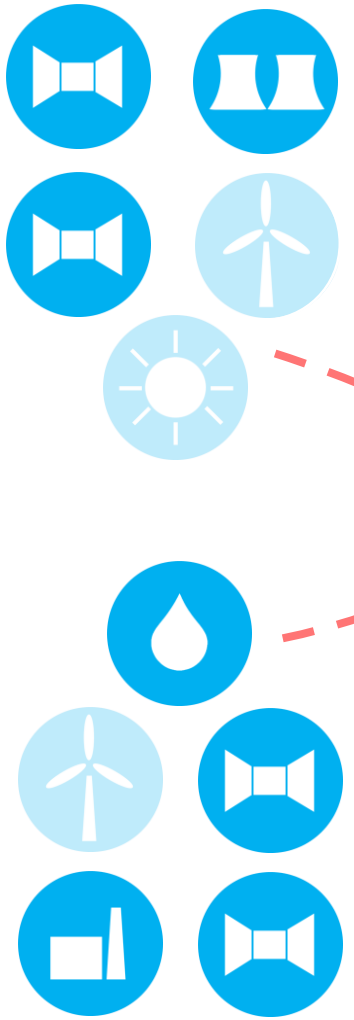
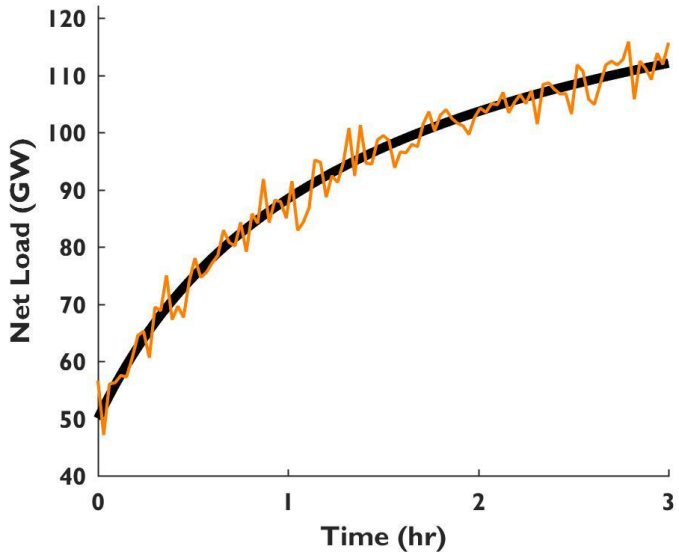
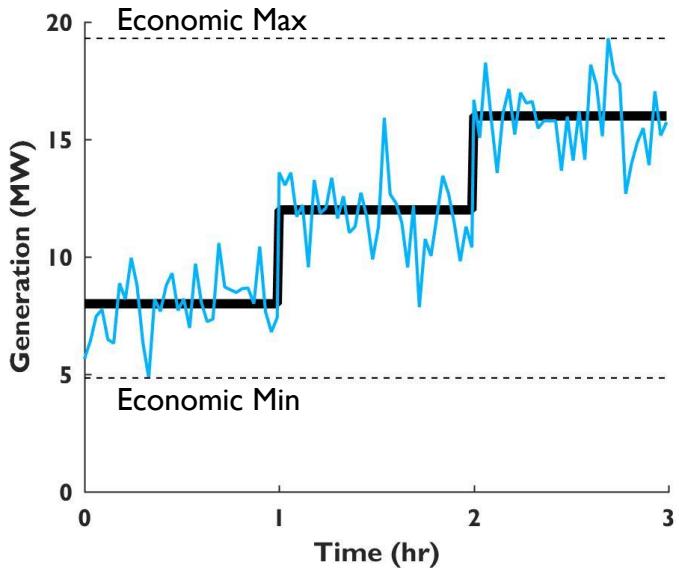


Ancillary Service Types

Regulation





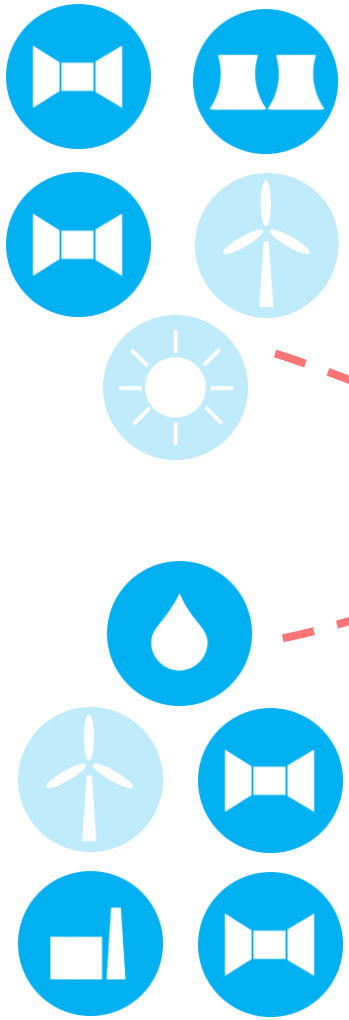


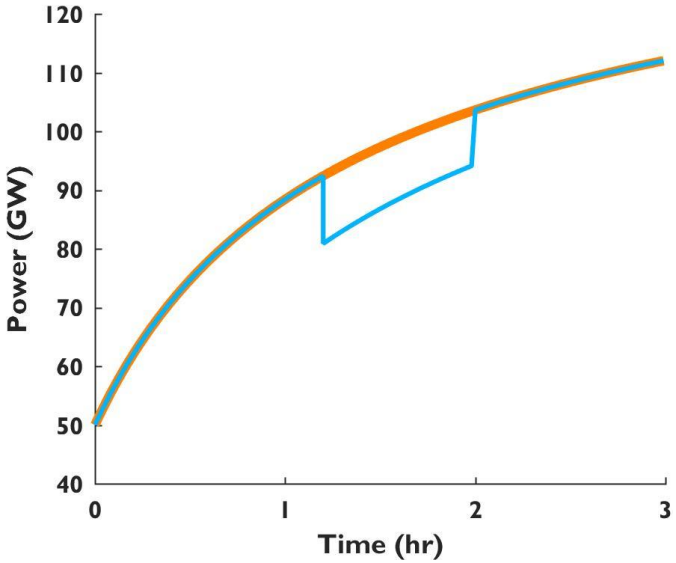
HE2 Reg Up Capacity

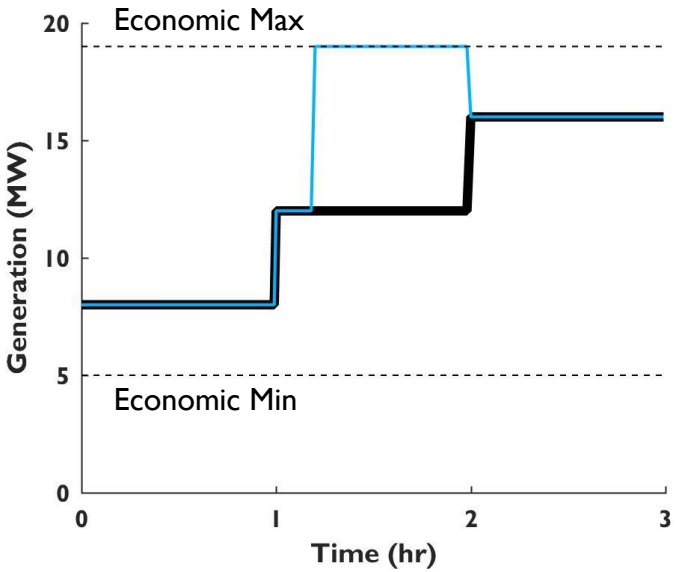
HE2 Reg Down Capacity

Ancillary Service Types

Reserves



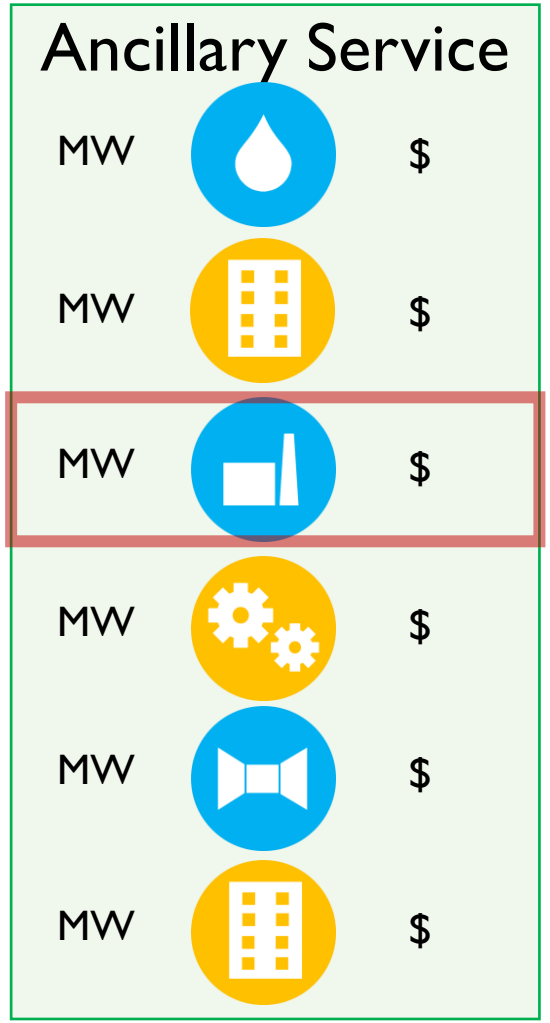




HE2 Reserve Capacity

Opportunity Cost Quantification

Opportunity Costs

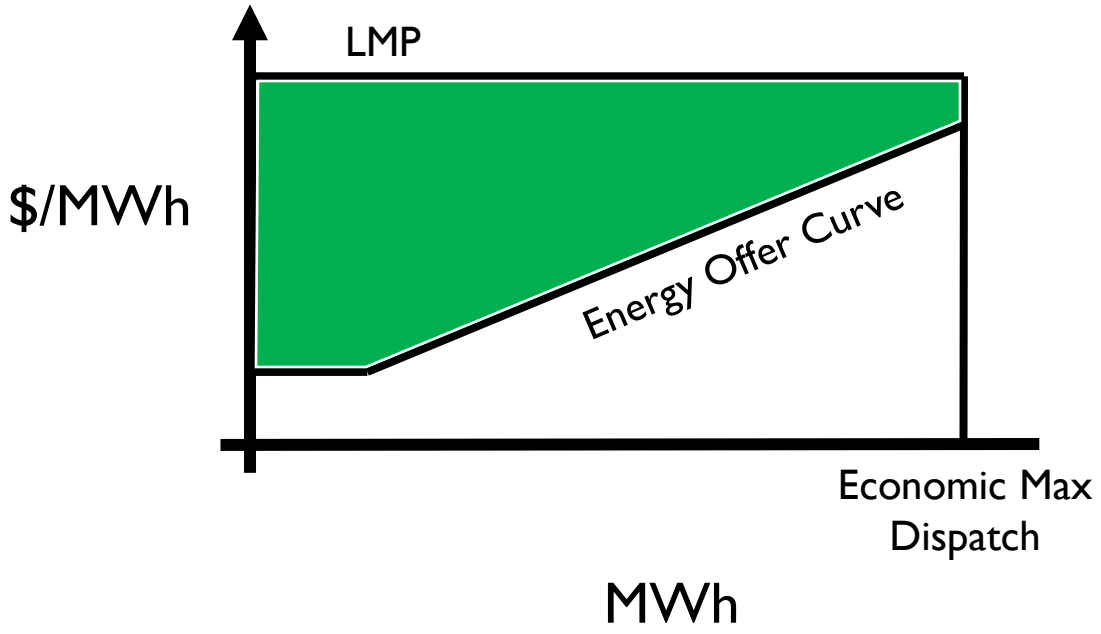


(65-75%)

Offer Cost = Operating Cost + Lost Opportunity Cost

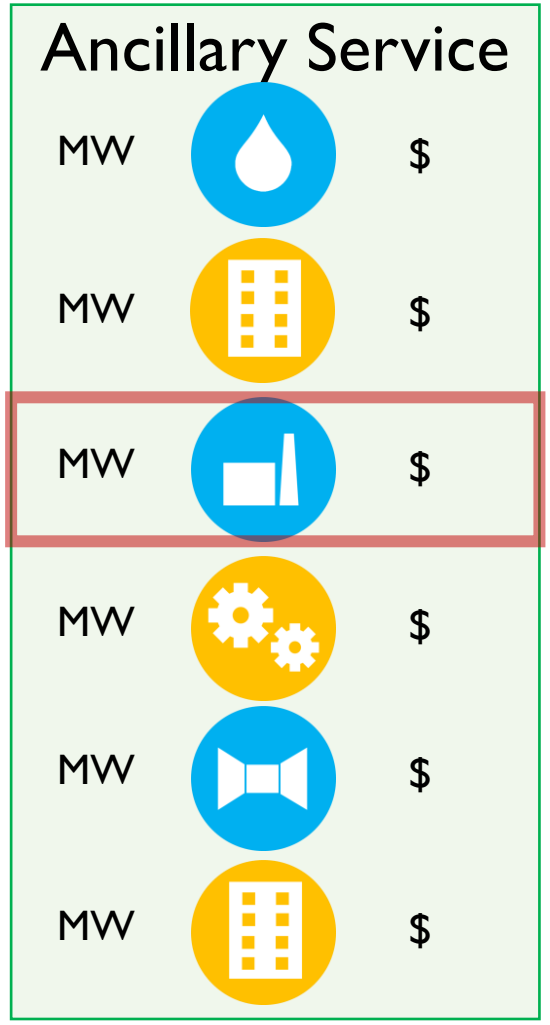
Additional fuel and efficiency loss

Forgone profit from energy market



Opportunity Cost Quantification

Opportunity Costs



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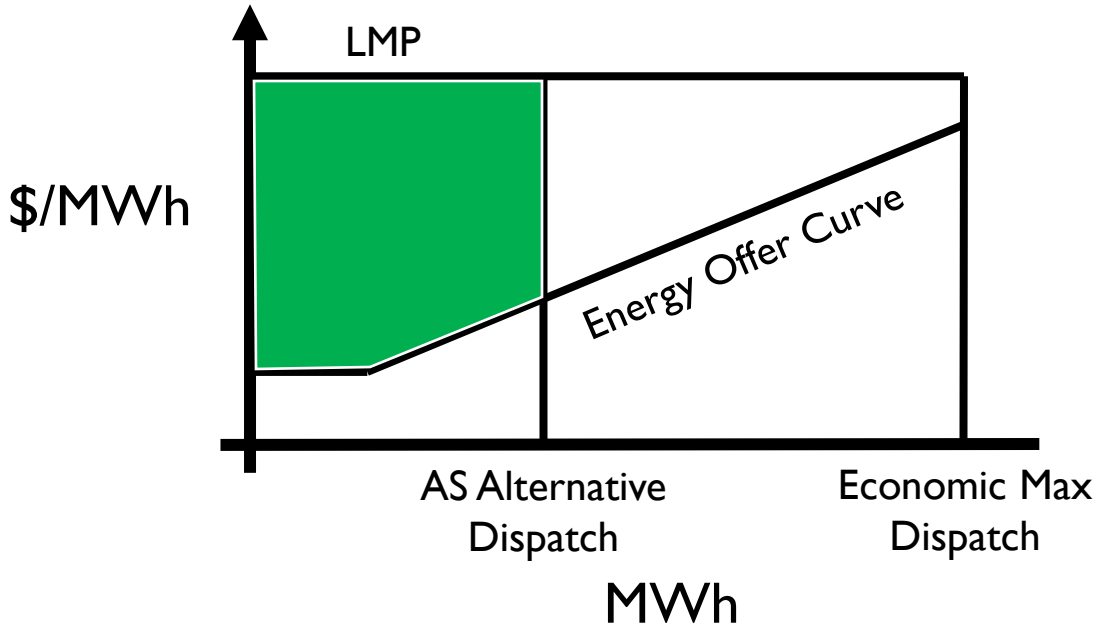
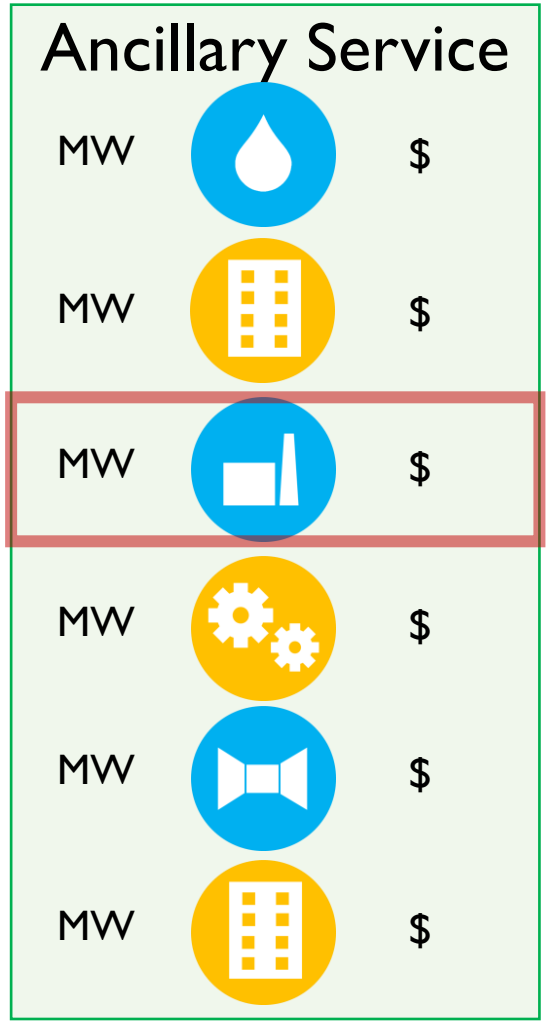


Opportunity Cost Quantification

Opportunity Costs



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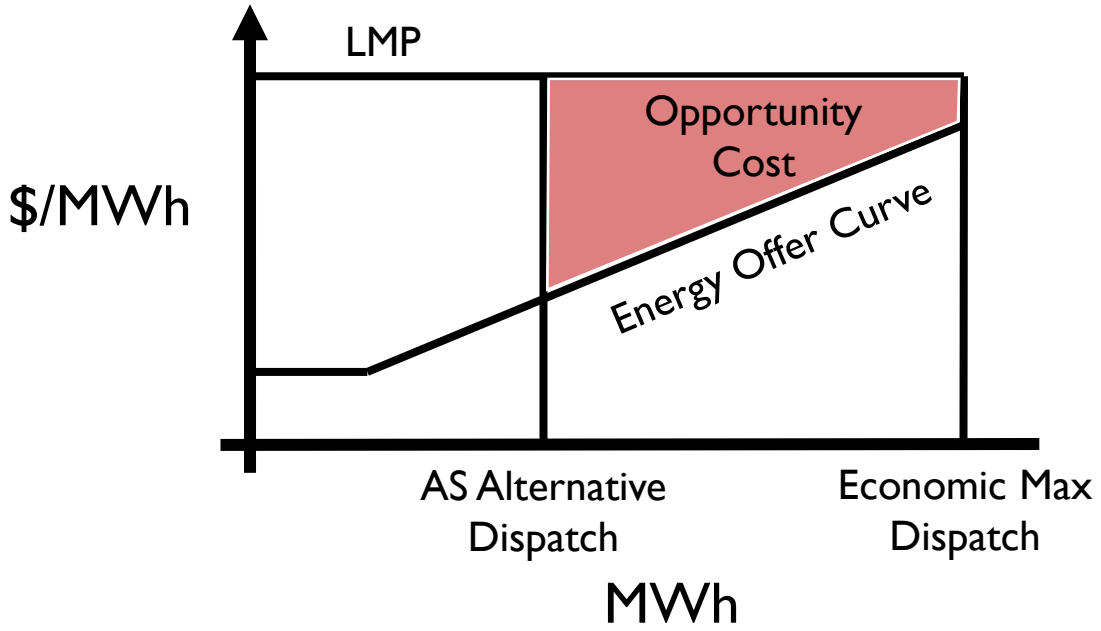


Opportunity Cost Quantification

Goals

1) Develop method for HVAC opportunity cost quantification
2) Produce opportunity cost bid curves for a given hour
3) Compare to ASMP

Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs

Generator: Decreased energy profits due to capacity used as ancillary service rather than sold into energy market.

LOC = Profit with economic max – Profit with AS adjustment

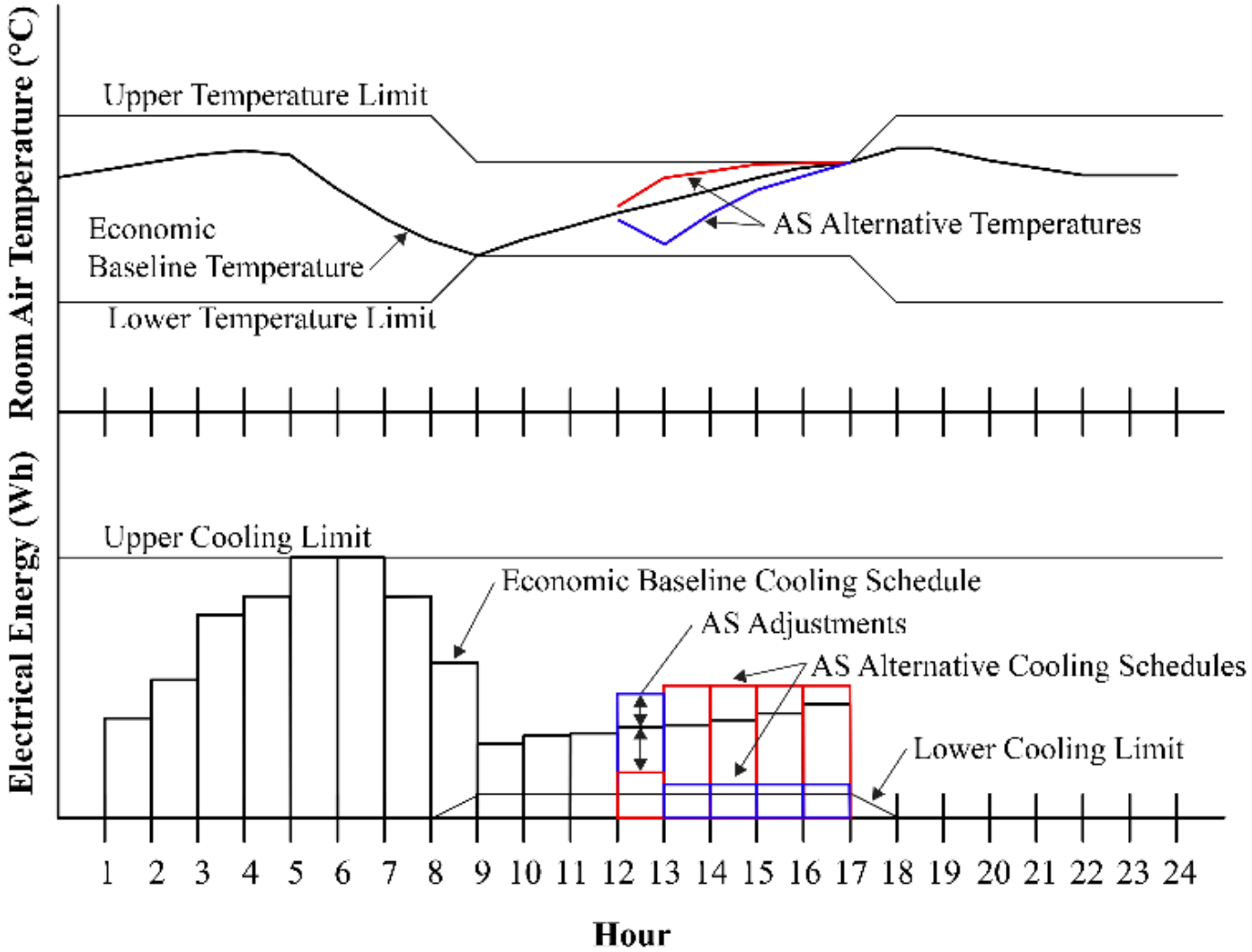
HVAC: Increased energy costs due to operating trajectories used for ancillary service rather than an economic minimum.

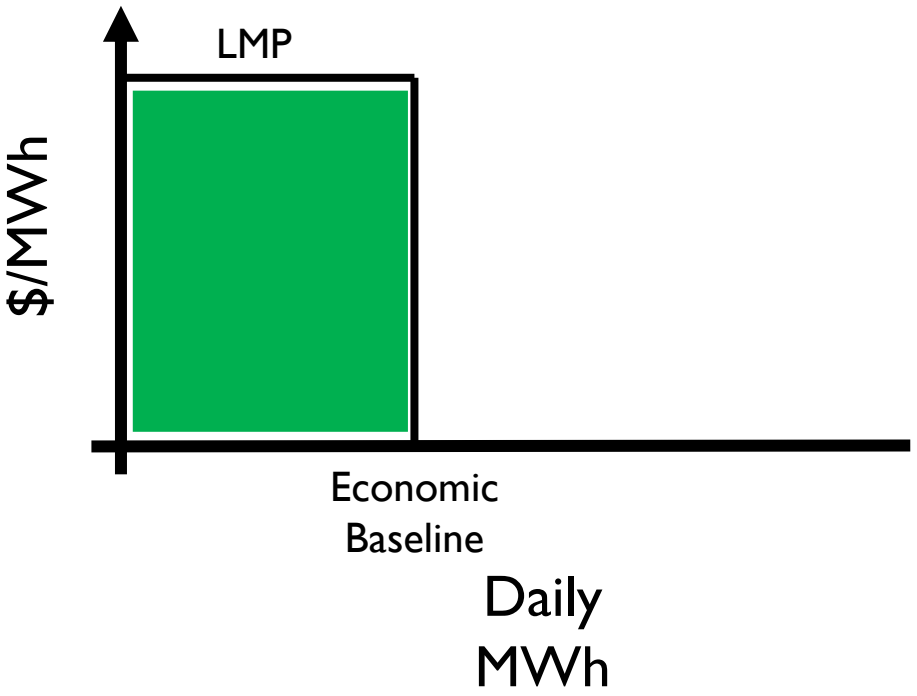
HVAC LOC = Cost with AS adjustment – Cost of economic baseline

Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs

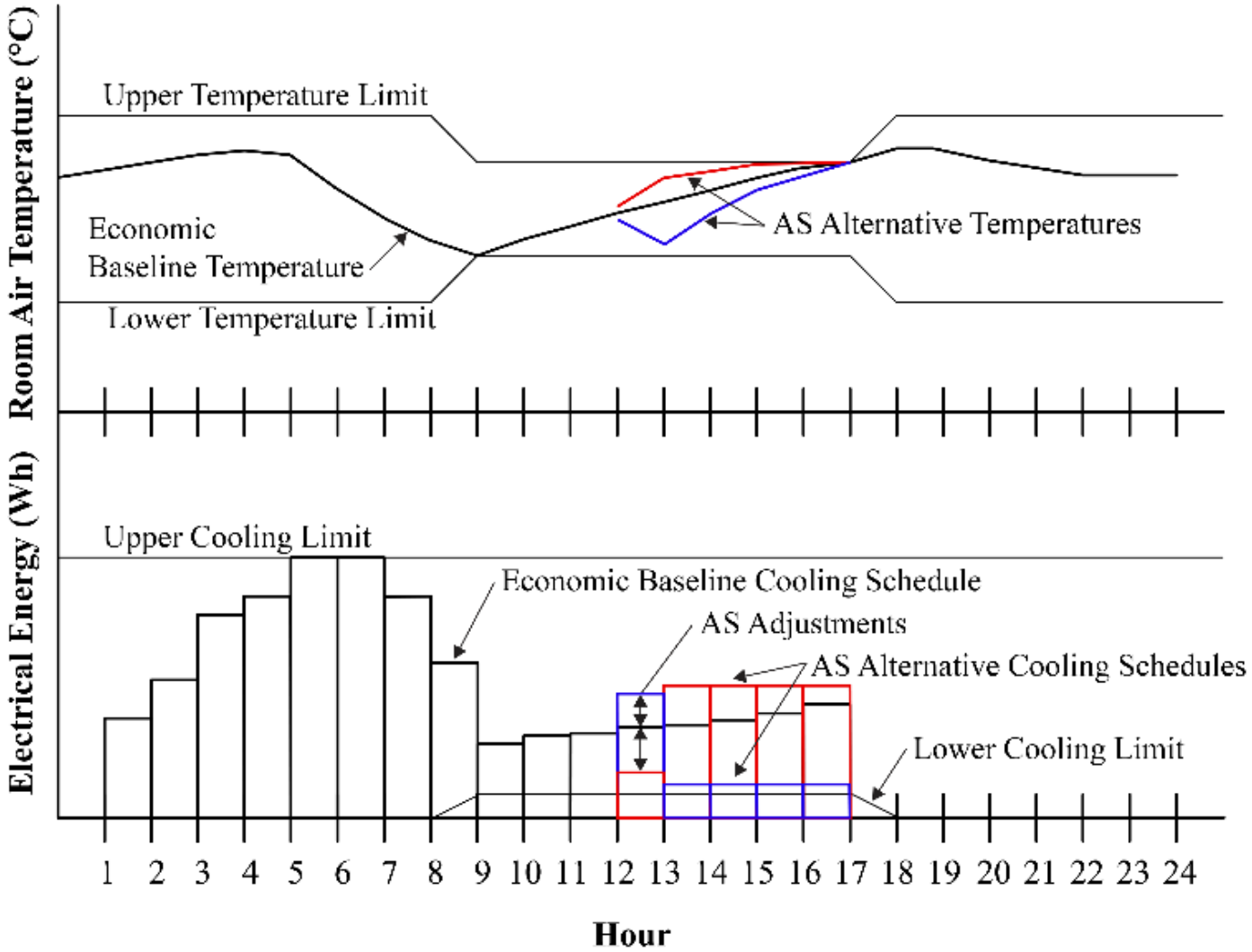


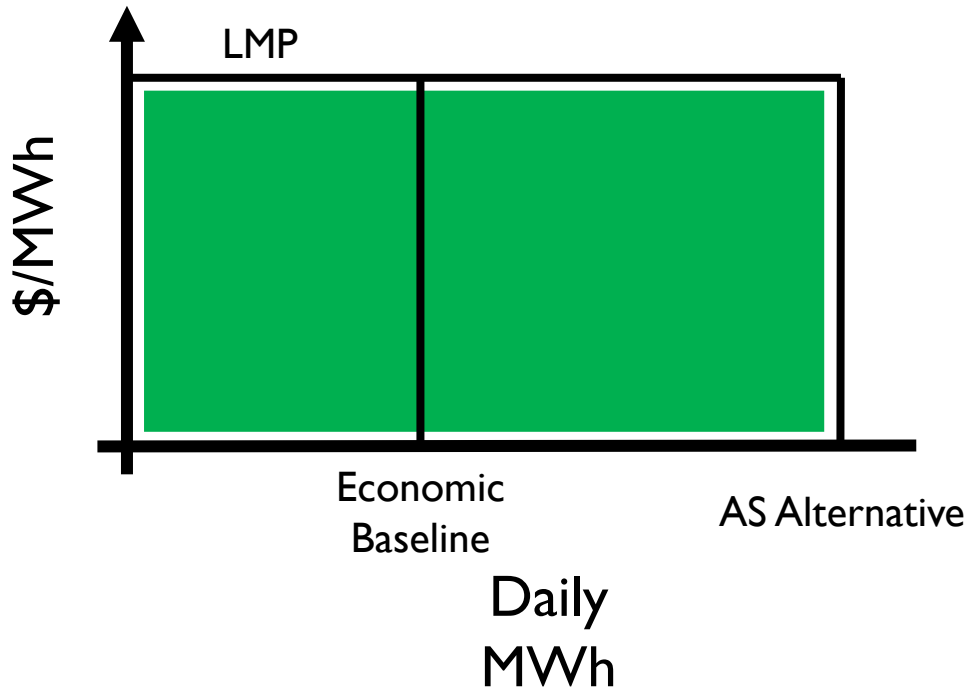


Opportunity Cost Quantification

Method

1) Define HVAC opportunity costs





Opportunity Cost Quantification

Method

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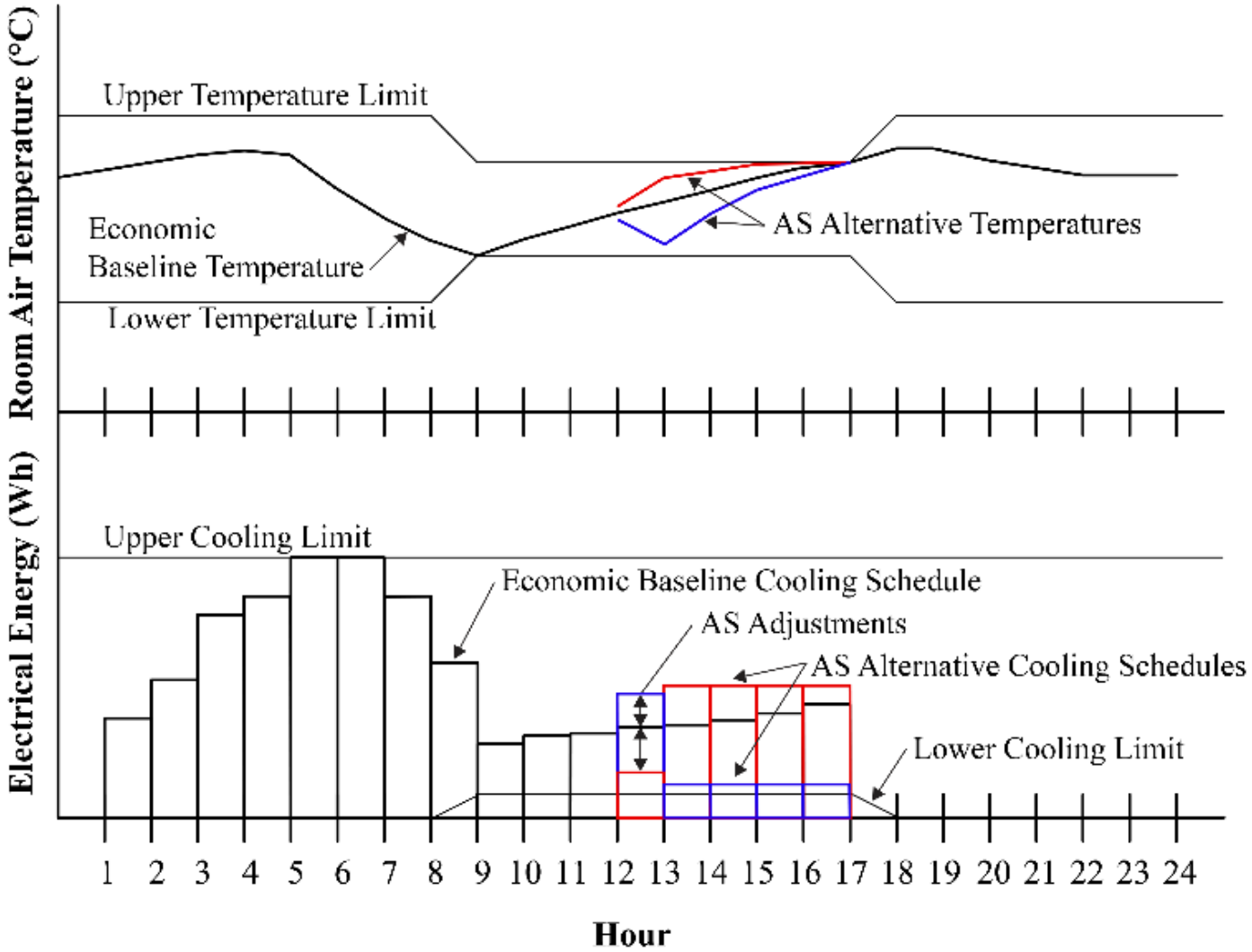
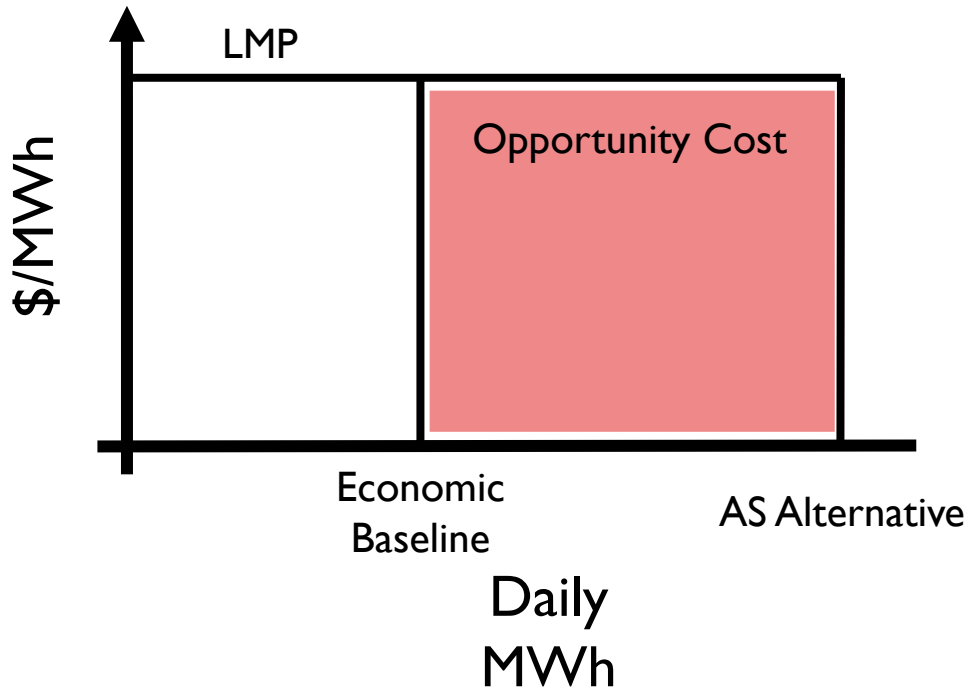
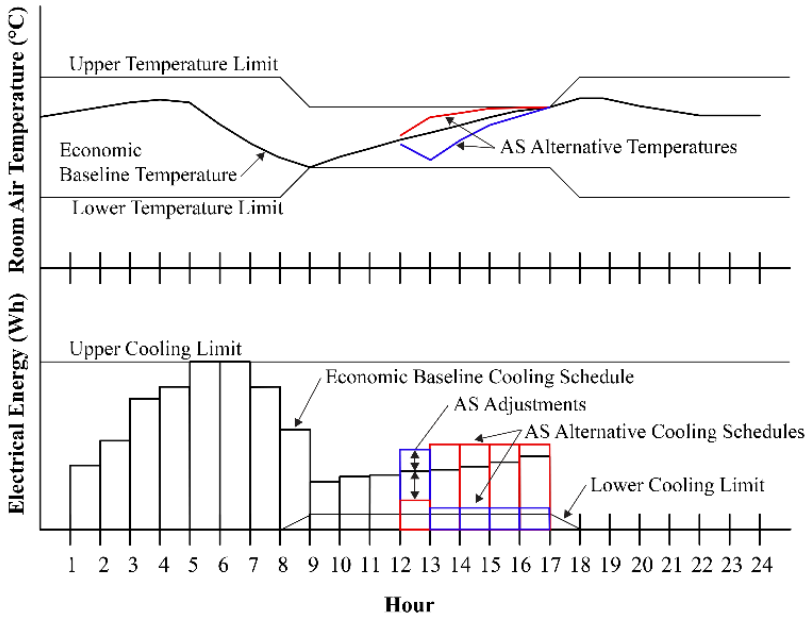




Opportunity Cost Quantification

Method

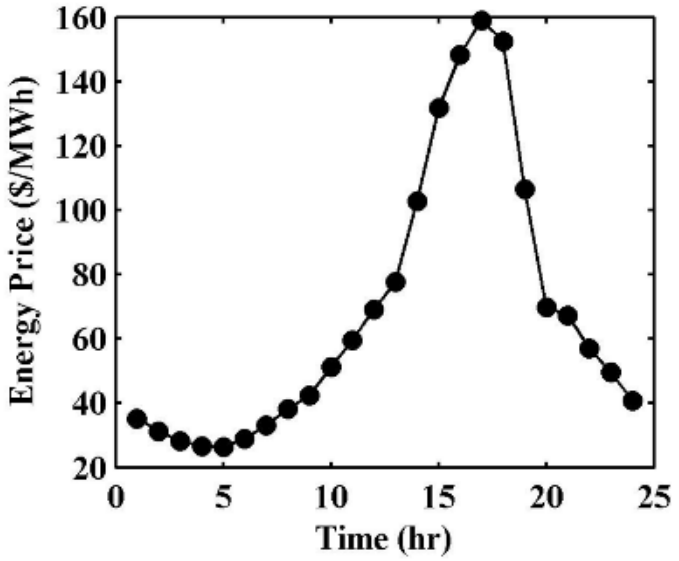
1) Define HVAC opportunity costs
2) Develop calculation procedure
   i) Calculate 24-hour economic baseline schedule by solving E-market optimization problem
   ii) Choose AS adjustment for hour
   iii) Calculate AS alternative schedule by solving modified E-market optimization problem
   iv) Calculate HVAC LOC by difference in daily cost



Opportunity Cost Quantification

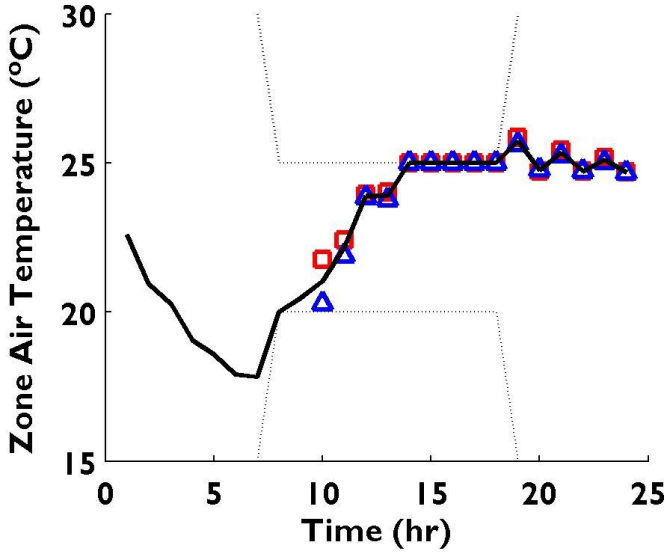
Method

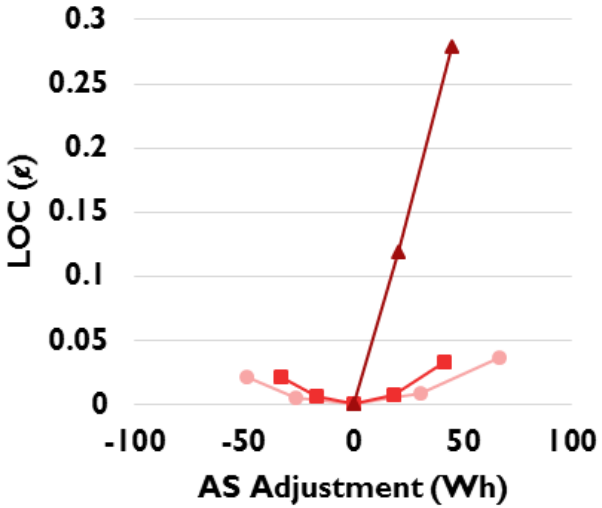
1) Define HVAC opportunity costs
2) Develop calculation procedure
3) Implement in MATLAB using E-market optimization



(PJM 2013)

Results – Single-Zone with Heat Pump

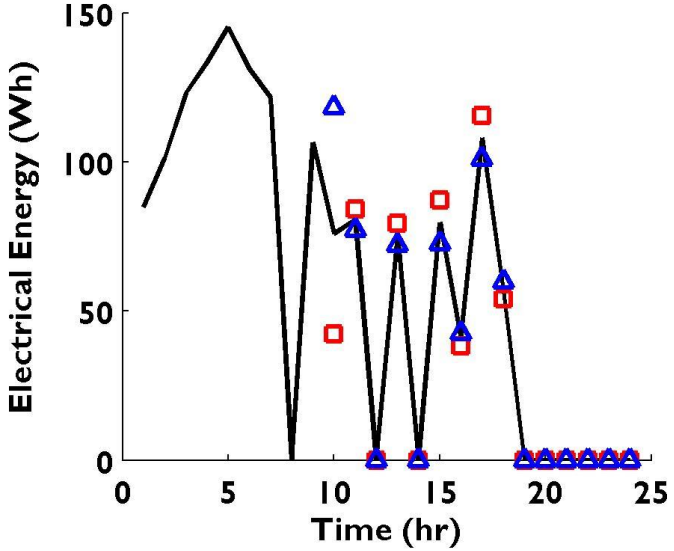


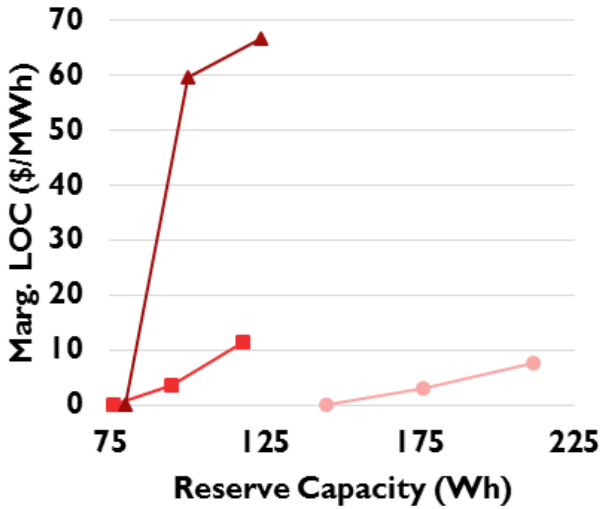


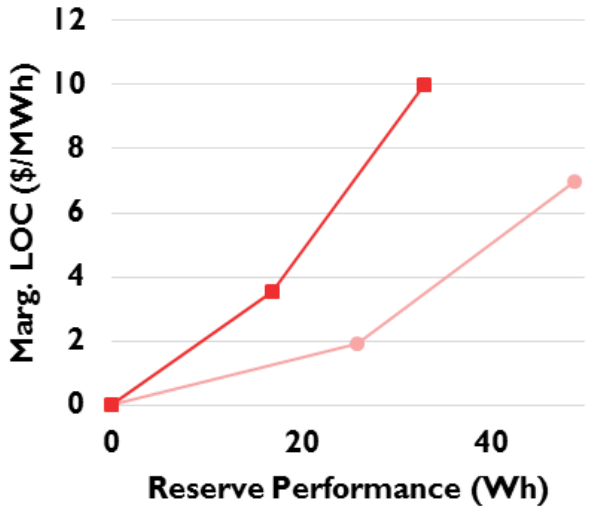
Hour 5

Hour 10

Hour 15







D. H. Blum, T. Zakula, and L. K. Norford, "Opportunity Cost Quantification for Ancillary Services Provided by Heating, Ventilating, and Air-Conditioning Systems." IEEE Transactions on Smart Grid, in review.

Opportunity Cost Quantification

Summary

1) Developed method for HVAC opportunity cost quantification
2) HVAC opportunity costs are comparable to ancillary service market prices

Future

1) Multi-zone buildings
2) Market integration
3) Experimental validation

This section based on (Blum et al. 2016b)

Research Questions

1) How do HVAC systems provide ancillary services?

   Dynamic Systems Modeling

2) Can buildings optimize a portfolio of ancillary services?

   Multi-market Optimization

3) Is there a price for providing ancillary services?

   Opportunity Cost Quantification

4) Does HVAC ancillary service provision scale with other energy storage?

   Quick ASDR Resource Estimation

Thank You!

Questions?

David H. Blum
dhb5014@mit.edu

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EFRI-SEED Award

ASHRAE Graduate Student
Grant-in-Aid

Martin Society of
Sustainable Fellows

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